TABLE OF CONTENT - DRUPSSUC - ANNEXES

ASSESSMENT OF THE URBAN PUBLIC PLACES IN MULTIDISCIPLINARY CONTEXT – PROPOSED METHODOLOGY

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This paper presents proposal of the methodology for the multidisciplinary assessment of urban public places which can be understood as an initial steps in territorial development policies on the scale of design and renovation of urban public space towards sustainable cities. Proposed method is based on transversal actions between different research fields, such a urban density, mobility, microclimate and pollution, vegetation and biodiversity, artificial lighting, water, acoustics and users, summarized and evaluated in a „transversality matrix". Our network deals with the problematic of public space on a national scale as it includes four interdisciplinary teams from all three regions of Belgium. This research is financed by the Belgian Federal Government (SPP-Politique Scientifique Fédérale) through the project "Development of the Urban Public Spaces Towards Sustainable Cities" (DRUPSSuC).

Keywords: urban public places, assessment, design, renovation, sustainable cities, transversality

1. INTRODUCTION

Design and renovation of urban public space is a complex problem, which undoubtedly require a careful multidisciplinary study and deeper understanding of the interactions between a large numbers of factors. The urban design theory and practice deals with different dimensions of social, visual, functional, temporal, morphological and perceptual characters which have a large impact on the situation in the place.

The term „urban design" was established in fifties as a replacement of the term „civic design", largely focused on the situating of the civic buildings, such as town halls, museums, concert halls etc. and their relationship to open spaces.[1] Urban design becomes somehow wider science which deals not only with distribution of new building objects but also carefully consider the spaces between them, to make them useful and enjoyable. In this way it is not simply an interface between the architecture and urban planning but it subsumes a number of other disciplines and activities.[2] This approach gives a possibility to include all important aspects in the design, creation or renovation of the cities. However, to be able to make a good proposal of criteria for the design, first appropriate assessment method have to be developed and validated. Our project is based on the multidisciplinary approach comprising the research results from eight specific fields where each research field proposes several subcategories for the urban public space evaluation from its point of view. Due to the detailed typology of each research field, large final number of data is expected and therefore convenient method for the global data analysis has to be established. The large number of data which have to be considered makes the research more accurate but also very challenging.

2. PROPOSED METHODOLOGY

2.1 Specific research fields

Urban density in general refers to the number of people inhabiting a given urbanized area and it shouldn't be understood as population per unit area what is usually called 'population density'. Urban density is an important issue in understanding the functionality of cities and it typically occurs in relation with economics, health, innovation, psychology, geography etc. Some studies tend to show, that higher density cities are more sustainable than the once with lower one, since these are often personal vehicles dependent. Several experts have shown the a strong correlation between the total energy consumption of a city and its overall urban density, however, this depends on the general transportation system of each country and might be different in cases of north-American cities where the living areas are often farer from each other than in the Europe.[3]

There are many ways of measuring the density of urban areas such a Floor area ratio, Residential density, Population density, Employment density, Gross density etc. An important issue is also the perception of the urban density as well, were the objective versus subjective density has to be investigated.

Urban mobility is a factor influenced by tradition, economical situation size of the city and many other factors. In our research it includes the development of hypotheses, established and confirmed by literature study and collected information. In addition, available statistical data and observations about the perception of the users on mobility choices and questionnaires in situ are being provided.

City users. Analysis on perception, appreciations and behaviour of the users in the urban environment is very important part of the whole study. The sociological approach consists of analysing the ties that have been woven between urban social conditions and the physical characteristics of open spaces. Several kinds of stakeholders are concerned by public spaces: the population (inhabitants, tourists), associations, decision takers (at municipal, regional levels), designers (architects, project authorities), developers, scientists, etc. As concerns the inhabitants and the population, the study identified: (1) their needs and behaviours (social practice) including the way they appropriate the places and their relation to the participative process; (2) the way they perceive public spaces, in view of their physical characteristics. Sociological methods in-situ and ex-situ are developed in terms of interdisciplinary relation. Methods ex-situ are covering the theoretical aspects and inspired by published studies on urban areas. In-situ methods including observation phase (for some cases we will use the video recording) and semi-directives interviews. This study will result in comparison of the assessment of the urban places by experts and users opinions.

Microclimate and air pollution. A microclimate has to be understood a as a local climate in a small-scale area, such as a park, square or a part of a city and its parameters, such as temperature, wind, rainfall or air humidity, may be slightly different from the conditions prevailing over the whole area. It has been investigated, that greater presence of condensation over urban areas can lead to higher amount precipitation in cities than the surrounding rural areas. Wind situation in urban areas strongly depend on the planning of the building masses which can cause high wind-speeds, when tall buildings create urban canyons in the prevailing wind direction or as the result of the increased surface roughness created by tall buildings, leading to local eddies and faster turbulent winds in between buildings. On the other hand, in case of carefully distributed building volumes, the wind-speeds in downtowns can significantly drop in comparison with surrounding rural areas due to the tall buildings, which can deflect and slow down the faster upper-atmosphere winds.[4] Another topic related to this field is the smog which is particularly dangerous during the colder months when the temperature inversions occurs and causes its staying closer to the ground and the water vapour condenses around the particles.

Climatic parameters of an urban site generally present substantial differences as compared to averages observed in a weather station in local pollution. For architects and urban planners it is convenient to take into account these local microclimate values while taking the architectural choices which can influence the general comfort inside and outside buildings as well as to lower the energy consumption of buildings. Recent technologies make it possible to perform an analysis of the microclimate parameters and to set their limits with a respect to the energy and environment. However, commercial simulation tools are very complex and often not affordable. This encourages us to develop a simplified practical tool intended specifically for decision takers and urban planers.

Biodiversity and vegetation research aims at the definition of the set of recommendations for the green structures to be adopted on the urban public space. Biodiversity includes all forms of life, as well as structural and functional aspects. Our approach is in general, not focusing on a target group (birds, insects, etc.) or a quantitative richness in plant species, but it is related to ecosystems with a goal of development of wildlife within the cities, or at least spaces accommodating this wildlife.

Vegetation is understood as the major support for plants and animals in the urban public spaces. Its management must be sustainable, i.e. adapted to local conditions, based on continuity, using possible natural process and conditions, avoiding the use of chemicals, meeting water and recreation necessities. At the scale of the cities, an advice related to creation of green structure networks and corridors is given, to promote the connectivity between green spaces for wildlife movements and to make easier contacts between city-dwellers and ‘nature’.

Water has been always strongly connected with urbanisation. People used to build their cities at rivers or lakes and the morphology of city was often adapted to the hydrographical situation and has often influenced the spatial and social structure of the city (upper and lower districts). Water is in general a factor of urban development in terms of the structuring (morphology, spatial identity), symbolism (individual and collective well-being; collective identity), a factor of identity, entertainment, aestheticism, recreation and spare-time activities.

This research looks for the relations between water, humans and the city in the sustainable development of public spaces. It also deals with natural and artificial hydrographical networks as well as underground water systems and permeability of ground. Re-introducing water in public spaces is adapted to the morphology of cities.

Artificial lighting in the urban environment is related to technical and qualitative elements of artificial lighting that could influence comfort, safety and feeling of security of pedestrians as well as environmental effects. Compromises in this field are necessary, since the harmful effects, and light pollution in the night have to be taken into account as well. There are studies which shows, that birds in some urban areas are singing the whole nights, since the light and noise pollution.[5]

Acoustics of the urban public places has to be understood more as a consequence or an aspect of the urban planning, rather than as an independent acoustical design. However this doesn’t diminish the importance of this field. In acoustical perception, sound sources don’t have to be visible to be heard and that’s why acoustics might act as one of the best descriptors of the activity in the urban public place.

When defining the set of best descriptors for the urban public soundscapes we work with the (1) objective acoustical parameters (quantities) obtained from recording in situ given as a number and a unit, and (2) semantic categories for context-related sound (by using the subject-centred methods), which can’t be described by numbers. The objective acoustical evaluation have to be understood as qualitative and quantitative analysis of sound. The quantitative description is about the noise assessment and uses the known methods of statistical noise analysis, whereas in the qualitative description of sound several psychoacoustical parameters (such a Loudness, Sharpness, Roughness and Fluctuation strength) are validated and new parameters concerning the binaural aspect of hearing are proposed.[6] The acoustical data are based on signal processing of the calibrated binaural sound recordings collected by using a soundwalk method, in view of determining statistical noise levels, psychoacoustical parameters and other variables.

2.2 Transversality matrix

It is very obvious, that the analysis of a large number of results is very difficult by using simple logic, inductive or deductive methods only. To find reliable conclusions, we try to find the best mathematical (statistical) method for our final data analysis.

We are convinced that the taken transversal research actions will bring an innovative view on the sustainable development of public spaces and the collection of the data in the global matrix system seems to be convenient. This system, proposes columns which represent the research categories (of each specific field) and rows are depict different public places.

Global Transversality matrix, shown in the figure 1 should allow us to apply a suitable statistical method on our data. In this way we will be able to run analysis in the horizontal and also in the vertical direction. Vertical analysis will help us to confirm our hypothesis and to find new correlations and interactions between different categories and specific fields. Horizontal analysis will allow us to analyze data from the point of view of an urban public space, such a comparison of streets, places or cities with each other. The initial division of the public places was made according to their position in the city, such as in the centre, urban or suburban part. The next division differentiates street, square and green areas (parks), but it is possible that new categories will be developed during the research on case studies.

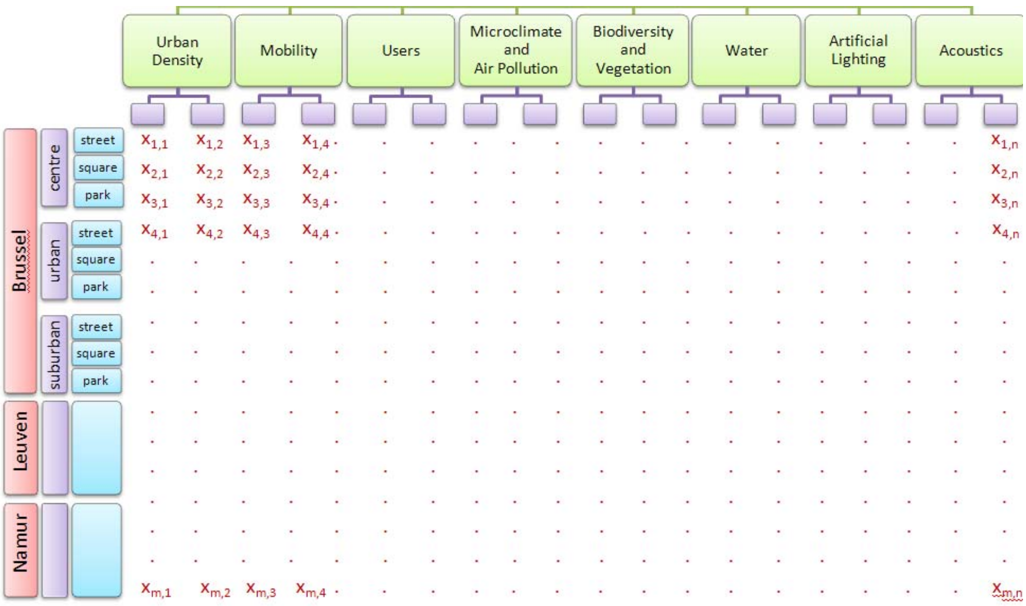

Fig. 1 Proposed global Transversality matrix

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Architecture for every listener

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1. ABSTRACT

'Ontwerpen voor Iedereen' (Universal Design, UD) beoogt gebouwen en omgevingen die toegankelijk, efficiënt en comfortabel zijn voor iedereen, en dit doorheen hun hele levensloop. In architectuur denkt men daarbij vaak direct aan toegankelijkheid. Akoestische voorwaarden kunnen echter ook een belangrijk effect hebben: de bruikbaarheid voor auditieve communicatie en het akoestisch comfort zijn belangrijke vereisten, zeker voor mensen bij wie de gehoorfunctie verzwakt is.
In onze studie onderzoeken we 'akoestisch comfort for iedereen' in de context van de Grote Aula van het Maria Theresiacollege in Leuven, die een beschermd monument is en aan een grondige opfrisbeurt toe is. De studie gebruikt state-of-the-art akoestische meet-, simulatie- en evaluatietechnieken om de diverse opties voor aangepaste ruimteakoestische voorzieningen tegen elkaar af te wegen.

2. INTRODUCTION & OBJECTIVES

Inclusive Design in architecture and urban planning tends to focus on accessibility of city environments, buildings and spaces by their users, but to our knowledge, acoustic comfort has received little attention so far. The impact on the built environment created by sound has a rather invisible character and thus in the stage of architectural design acoustical aspects are often suppressed. As a result, most of the acoustical problems usually show up only later, once a building or space is built and already used. Some of the acoustical defects can be solved later, but most of them cannot be repaired and they just degrade the quality of an otherwise nice brand-new building. In this way many buildings suffer from acoustical problems and acoustical comfort is often not reached, not even for healthy listeners.
Hearing provides us with auditory information, which is important in human communication and spatial orientation. Good speech understanding and localization of sound sources is crucial. Bad speech intelligibility during the educational process leads not only to tiredness and lack of concentration among students, but people who do not hear well can even end up in social isolation as communication becomes difficult. Legislation is usually less strict with regard to acoustics than in relation to other building physics categories, and moreover differs from country to country.
The attitude of different countries towards Inclusive Design in acoustics varies from prescription of imperative guidelines to simple recommendations (Karabiber and Vallet 2003). However, little attention is paid to the diversity in people's hearing capacities and needs in general.
The study reported on in this paper attempts to contribute to the knowledge base by exploring the idea of acoustic comfort for all listeners in university education.

3. PROGRESS & ACHIEVEMENTS

3.1 Interviews

To get an idea about the acoustical comfort in the auditoria at K.U.Leuven, a series of in-depth interviews were conducted with various users/experts, e.g. students and personnel with a hearing impairment, students with a visual impairment, and students who attend the University for the Elderly. All interviewees were asked to nominate the best and worst auditorium in terms of acoustic comfort, and to indicate problems they experience when attending lectures. During the interviews, the 'Grote Aula' (Big Auditorium) of the Maria-Theresia college was labelled by several users as the worst. This has motivated us to select the Grote Aula as reference auditorium for our case study.

3.2 The Grote Aula of the Maria-Theresia college

The Grote Aula of the Maria-Theresia college is situated in the city centre of Leuven and since 1975 is officially listed as protected monument. In the past, many interesting activities were performed in this college to which the auditorium also belongs. One of the most famous events was the seminar of Theology in this former Jesuit college accommodated by Maria-Theresia (in 1778).

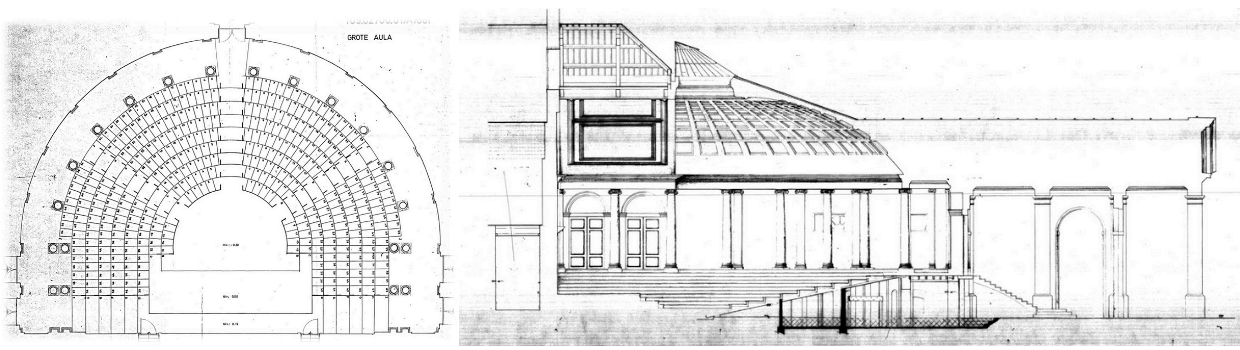


Fig.1 Ground plan and cross-section of the auditorium as found in the archives (De Leye & Dooms 2007)

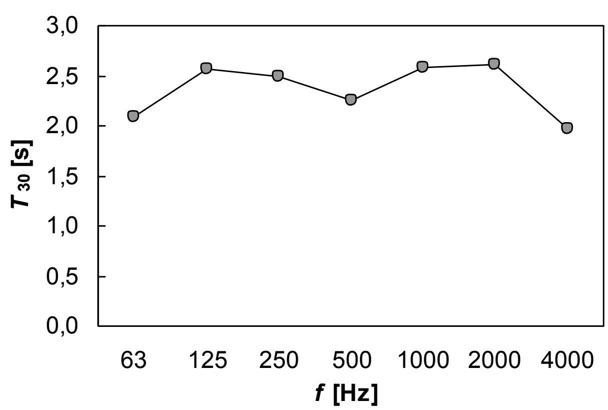
The Grote Aula is a neo-classicist auditorium, designed by Martin Hensmans, with a half-round ground plan. The volume of the auditorium is 3600m^3 and contains around 500 seats. Nowadays the Grote Aula accommodates undergraduate and graduate students on a daily basis. Once a week, students of the University for the Eldery attend lectures here, and at night or in between semesters, the auditorium is available for musical activities. Both types of events, lectures and concerts, require different reverberant conditions. A speaker demands a much shorter reverberation time than a musical performance, but in both cases low levels of background noise are desired. For people with hearing disabilities are the limits of speech intelligibility even more pronounced (De Leye & Dooms 2007).

Fig.2 Photo of the interior of the Grote Aula

Interviewed users/experts especially complain about the difficulty to clearly understand the speaker during lectures. Comparison with other auditoria at the K.U.Leuven confirmed that the acoustic conditions in the Grote Aula show considerable room for improvement. The planned renovation in 2009 provided extra reason to submit this auditorium to an in-depth analysis and to propose interventions that improve the acoustic comfort for all.

3.3 Measurements

Measurements in the Grote Aula were performed on 16 receiver positions chosen in the audience area (Fig.3). Firstly, to obtain the most accurate information about the reverberation time and sound pressure level distribution in the room, impulse response measurements according the ISO 3382 were performed by using omnidirectional sound source B&K 4295 and omnidirectional microphone B&K 4130.
Later, for calculation of interaural cross correlation coefficients (IACC) describing the spaciousness, measurements with artificial head on the same 16 positions were done.
A third experiment was based on usage of the directional sound source (RASTI-speaker) with directivity close to a speaking person, to get the most realistic impression about the speech transmission index (STI) values.



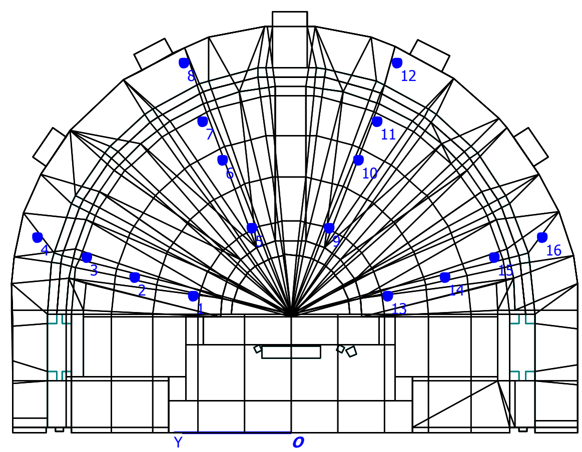


Fig.3 Average reverberation time T_{30} [s] as measured (left). Ground floor plan of the auditorium with 16 receiver positions (right)

Impulse response measurement in the Grote Aula has confirmed too long reverberation. Measured T_{30} has reached 2,4 seconds, which is too long not only for lectures but also for music and if we like to provide acoustical comfort for all, this value should be diminish drastically. Since no norm exists we have to base our proposal on experience. For speech we would like the value of reverberation time RT = ca. 1 second, while for music 1,8 seconds would be ideal. Here the administrators and management have to decide what is preferred.

3.4 Simulations

Simulations of a virtual 3D model of the auditorium were performed in the ODEON ®software v.8, in nine alternatives. These alternatives were based on different combinations of additional sound absorption in order to reduce reverberation time and to improve the speech intelligibility. As the auditorium is a historically protected monument, discrete solutions of extra absorption addition were provided.
The optimum amount of sound absorption in the room usually depends on the activity for which the room is designed. The Grote Aula is an auditorium (for classical lectures) but it accommodates also musical performances. For this reason we explored the possibility of applying movable absorption, which can be adapted to the intended activity.
During the analysis of the data, five different aspects were considered:

1. speech, for which we like the value of reverberation time ca. 1 second and speech intelligibility defined by STI value > 0.6
2. music, where we like the reverberation time around 1,8 seconds
3. maintenance, which describes how easily materials can be cleaned and how fast they get dirty
4. flexibility, which refers to adaptability of the space for music or speech respectively
5. replacement, which shows how easily can be additional absorption removed or replaced.

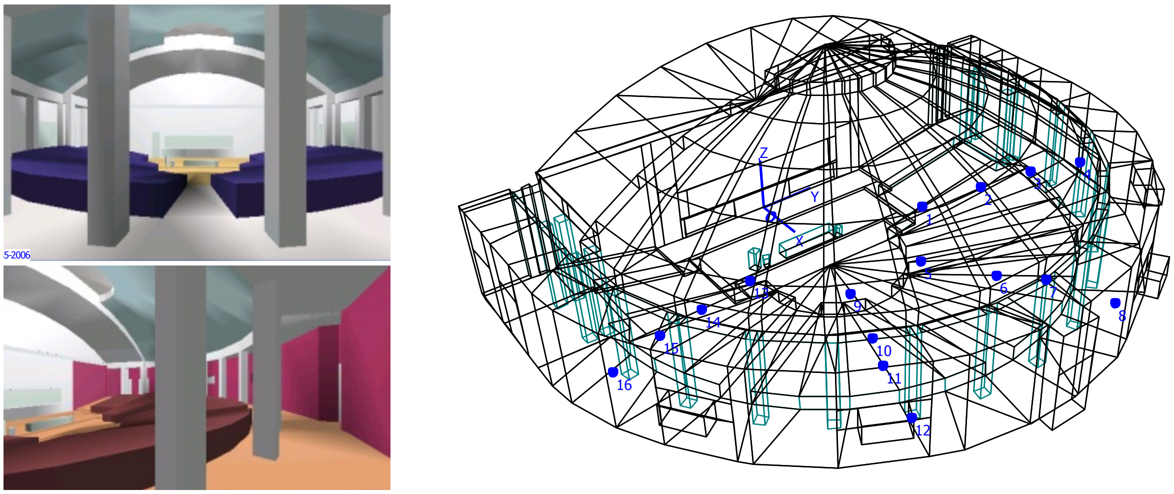


Fig.4 3D computer model of the Grote Aula as used in the acoustical simulations

In the acoustical renovation proposal, the following changes were considered:
a. replacing the present leather-covered seats by slightly stuffed seats covered with cloth
b. replacing the existing linoleum floor by carpet (suggested by the Technical services)
c. applying an acoustic plaster on an acoustic absorption layer to the wall
d. placing removable sound-absorbing wall panels covered with cloth
e. hanging curtains along the wall
f. applying an acoustic plaster to the ceiling above the gallery
g. applying a thin acoustic plaster to the cupola and vault above the podium.
Results form all alternatives are summarized in the Table 1.

Table 1. Comparison of the simulated alternatives

		comparison of the alternatives									
	current situation	Alt.1 (a)	Alt.2 (a,b)	Alt.3 (a,b,c)	Alt.4 (a,b,d)	Alt.5 (a,b,e)	Alt.6 (a,b,c,f)	Alt.7 (a,b,c,f,g)	Alt.8 (a,c)	Alt.9 (a,f)	
music T_{30} [s]	2,48	2,44	1,72	1,18	1,10	1,26	1,17	1,01	1,90	2,22	optimal
speech STI [-]	0,45	0,46	0,51	0,58	0,58	0,59	0,59	0,62	0,52	0,48	
maintenance											moderate
flexibility											
replacement											weak

4. CONCLUSIONS

Measurements in situ confirmed the need for improvements in the Grote Aula from the room acoustical point of view. With the help of acoustical expertise in room acoustic simulations, nine alternatives related to acoustical improvements taking into account the auditorium's historic character were evaluated with respect to five aspects, e.g. speech intelligibility, music performance, maintenance, flexibility and replacement. Analysis shows that the ideal solution does not exist. Depending on the priorities, one can select the most appropriate solution from Table 1. However, application of any additional sound

absorption to the room will reduce the sound levels on all positions in the audience areas and thus a well-designed loudspeakers system to amplify sound, will be necessary.
In general, results of the given case study may give an idea when designing or renovating similar places in the future. As such, the study contributes to understanding the importance of acoustic comfort for all, and offers an example of desirable solutions.

Acknowledgements

The case study reported on is based on the Master thesis of Karolien De Leye and Eva Dooms. Special thanks are due to the experts/users, the Technical services of the K.U.Leuven, and KIDS (Royal Institute for Deaf and Speech Impaired).

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Elaboration of multicriteria decision-aiding tools for the conception of urban public spaces

Proposed methodology

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A study dealing with complex problems, such as the question of public spaces, cannot consist of distinct sectors that can be managed separately to get an optimal response. It must be done by transversal approach which breaks down the barriers between different disciplines by connecting them to each other for their mutual enrichment. The aim is to pass from simple maxima to a composite optimum. It is a question of passing from a parallel multidisciplinarity to a real transversality. It is like the cross-functional element of a structure which triangulates this one and protects its stability. With its transversal point of view, this paper proposes a step by step methodology for elaboration of multicriteria decision-aiding tools for urban public spaces conception. The expected results, both practical and scientific, are also presented.

Keywords: urban design, transversality, multicriteria method, aiding tool, methodology

1. INTRODUCTION

The public spaces and the cities are highly complex areas. The conception of these, places of life and sociability, depends on numerous disciplines. Unfortunately, the decision-maker or the designer works alone or in small teams. As a consequence, the former hasn't all the necessary background to deal in an effective and satisfactory way with the global and transversal conception of urban public places. With regard to the transversal principles of the sustainable development and its implications on the urban conception, the decision-maker's difficulty is even more obvious.

When a multidisciplinary and complex problem is faced, the right way to success is to enrich the information in all the domains other than the ones we initially take more particularly care about. This way strengthens all the domains. It is a question of passing from a parallel multidisciplinarity to a real transversality. It is like the cross-functional element of a structure which triangulates this one and protects its stability.

Naturally, public place projects and town planning are transversal. The disciplines and the involved parameters strengthen or weaken each other. The urban necessities as physical, physiological or psychological as well as social, cultural, political, economic or environmental, meet, collide or are linked, according to the chosen conception options and their territorial integration.

1.1. Stake

This paper presents a methodology for the elaboration of multicriteria tools. These are decision-making instruments dedicated to enrich the processes of conception of urban public places. Moreover, they are supports to decide between various options. The use of such strategic tools allows passing beyond the highly rigorous compartmentalized visions of the various public or private stakeholders. These visions have to be avoided. They lead to decisions recovering from simple maxima and being often erroneous in a global approach. A contrario, a correctly built transversal multicriteria approach leads to solid decisions based on a right multidisciplinary compromise.

1.2. Contents

Firstly, we will present the way to do multicriteria studies.

Secondly, we will develop the steps for the elaboration of the selected models. We will deal successively with the choice of criteria, with their formal expressions and with their weights.

Then, we will present the expected results and the scientific expectations which are linked to.

2. MODELS CHOICE

Two strategic approaches are offered by the designer or the decision-maker who intends to deal with the questions of public places conception in a “mutlicriteria” way.

2.1. Aggregative benchmarking approach

The first approach type follows the way of a benchmarking logic which can use a partial or total aggregative way.

Aggregative benchmarking approach presents an estimation of the distance between a solution and its theoretical optimum. However, this kind of approach causes the addition of different factors with loss of nuances. So the aggregative approach has the weakness to engender indifference, incomparability and compensation problems which can distort the conclusions that we could obtain from this method.

2.2. Ranking approach

The second approach type is a ranking logic which ranks the options of conception. Like the aggregative logic but with other significance, this classification can be partial or total. The multicriteria methods are the expression of this kind of approach. They express preferences between possible solutions and they integrate all types of factors as they are. These methods allow passing from simple and isolated maxima to a right multidisciplinary compromise.

Among the multicriteria methods presented in the literature, we focus on the Prométhée I and II methods. Prométhée is the acronym of Preference Ranking Organisation Method for Enrichment Evaluations. The Prométhée methods build mathematical outranking relations according to preference intensities expressed by ingoing and outgoing flows.

The principle of the Prométhée methods consists in establishing a process of numerical comparison of each action with regard to the other considered actions. It calculates the merit or the shortcoming of each action with regard to the other actions. The result of this comparison leads to the orderly ranking of these. We shall not present the mathematical black box of the Prométhée methods but only the way to implement such methods.

From the multicriterion point of view, the possible actions that can be considered are "any project of conception or renovation of an urban public space".

The Prométhée I method deducts a partial ranking relative to the various ingoing and outgoing flows. An ingoing flow is the measure of the way an action outclasses all other actions. An outgoing flow is the measure of the way that an action is dominated by all other actions. A partial ranking takes into account the fact that certain actions cannot be totally ordered because they are incomparable.

Prométhée II is a method which takes another way than the first one. This method determines a total ranking. Thanks to the technique of the net flows, Prométhée II orders all the actions even if they are incomparable.

These two versions of Prométhée complement each other. One of them presents a total ranking, the other ensures to qualify this ranking by highlighting incomparability.

2.3. Double approach

There is an interest to deal with the conception of public spaces by practising both approaches simultaneously. The benchmarking approach confronts considered actions with absolute levels of quality. The ranking approach measures the preference level of a solution without being simplistic in the treatment of the various factors.

3. HYPOTHESIS

Unfortunately, time and means are not infinite. So the multicriterion exhaustiveness cannot be a standard. So in a goal of performance, it is good to opt for an approach following the law of Paréto or principle 80-20 which namely focuses on crucial factors (approximately 20%) that influence the largest part (80%) of the objective.

The most relevant domains of studies should deal mostly with spatial organization, mobility, architecture and built environment, materials and techniques, vegetation and water, psychological and physiological comfort, and uses.

3.1. General implementation

From a climate to another, from a culture to another, from a city to a contiguous one, necessities can vary. Also, there is no absolute tool or multicriteria method because criteria and weights vary tremendously. Consequently, we will not venture in this paper to congeal the contents of methods. We will rather propose a methodology to construct successful multicriteria tools adapted to each public space conception problem.

3.2. Strategic objectives

Although the conditions are different according to different places on earth, there is a certain universality about the transversal objectives for the up to date sustainable town planning. These objectives should guide the criteria choice and the weights applied to each of these.

The main transversal objective is the improvement of the quality of urban life. Four underlying strategic objectives are : the development of urban areas as places of sociability; the development and encouragement of public spaces uses which limit the nuisances and favour the environmental benefits; the development of urban places as structuring elements of urban areas; the development of natural spaces protecting natural cycles in the city [1].

4. CRITERIA CHOICE

As indicated by Roy [2], the family of the selected criteria must answer the requirements of exhaustiveness, cohesion and non-redundancy. Moreover, the criteria must be perfectly independent from some of the others. For the criteria selection, it is highly recommended to opt for an approach according to the law of Paréto already expressed previously in this paper. In regard of the numerous disciplines dealing with the question of town planning and public spaces, the Paréto principle is crucial, otherwise the number of criteria rapidly increases.

4.1. Structuration

Contrary to the aggregative approach, the Prométhée methods cannot deal with numerous criteria at once. Unfortunately and in spite of Paréto, the conception of urban public places always generates a significant number of criteria. Then, Prométhée methods cannot be envisaged as they are. A solution is to structure the problem in an arborescence of particular methods parts of a global method. The results of each of these particular methods are criteria for the global final method. These criteria are the preference flows corresponding of the particular methods. For example and like presented in figure 1, an easy solution is to segment the global multicriteria method in sub-methods according to the scales of study.

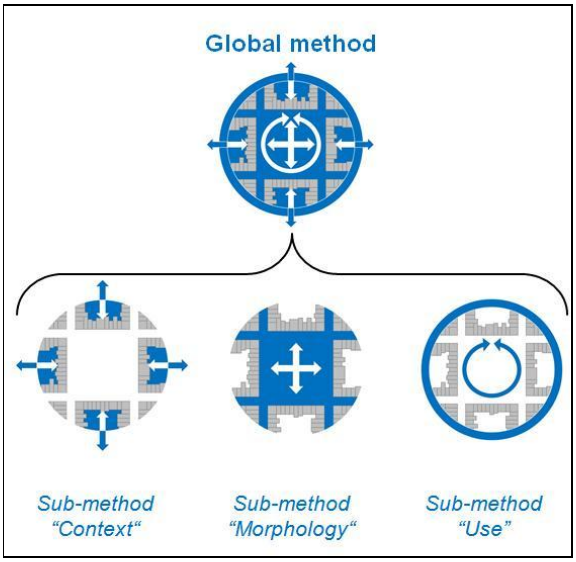

Figure 1 : Proposed arborescence of multicriteria (sub-)methods for urban public spaces conception

Three scales of study are proposed: the context, the morphology and the use. The context is about all which concerns the space but is not really a part of the space. That's the integration of the place into the city. The morphology is constituted by all which materializes the place. The third one, use, deals with all which is immaterial but creates the space inside. The intersection of these three scales is the public place envisaged transversely.

4.2. Benchmarking expression

Beyond the intrinsic nature of every criterion, it is necessary to express each of these in an exploitable format. It must be exploitable by a benchmarking logic measuring the gap between an option and a theoretical optimum.

The selected way expresses each criterion according to a discrete scale with ten levels from "1-null" to "10-optimal solution ". The table 1 presents an example of this mechanism. It deals with the energy consumption of the street lighting devices. The value 10 corresponds to the reachable optimal value with the current techniques. The value 1 corresponds to the threshold from which the consumption becomes unacceptable for the available illumination.

Each criterion which is expressed on similar scale products is an easy interpretation of the distance from this one to its optimum. A proposition of graphic representation is presented in the section below concerning practical results.

Table 1: Street lighting energy consumption – example of a criterion benchmarking expression for aggregation

Minimum [W/m²/10lux]	Maximum [W/m²/10lux]	Assessment	Score
< 0,2	0,2	Optimal	10
> 0,2	0,3	Very good	9
> 0,3	0,4	Good	8
> 0,4	0,5	Quite good	7
> 0,5	0,6	Average	6
> 0,6	0,7	Quite unsatisfying	5
> 0,7	0,8	Unsatisfying	4
> 0,8	0,9	Bad	3
> 0,9	< 1	Very bad	2
1	> 1	Null	1

4.3. Prométhée expression

For every criterion, Prométhée compares the actions by pair and measures the preference intensity "H(d)" of one with regard to the other, according to the difference of assessment "d" between actions for this criterion. The expression of this intensity H(d) is called preference function. The function H(d) can have various forms and depends on certain parameters. The six families of preference functions named "generalised criteria" used in the Prométhée methods as well as their parameters are presented in figure 2. The type I corresponds to the "real criterion", type II is the "quasi-criterion", the type III is the "criterion with linear preference", type IV is the "criterion by levels", the type V is the "mixed criterion" and finally the type VI is the "Gaussian criterion".

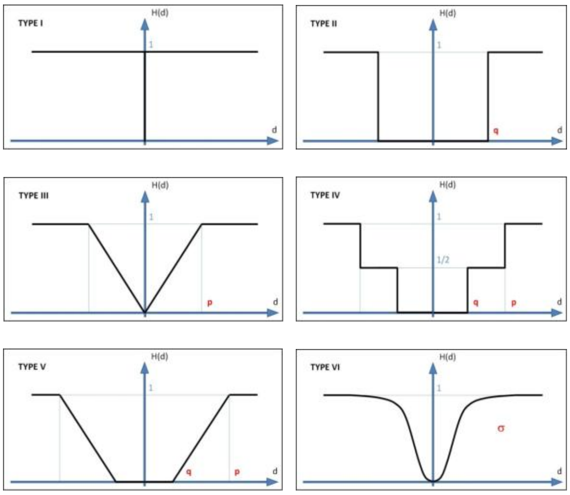

Figure 2: Generalised criteria for Prométhée methods

There are three parameters relative to the generalised criteria. They are considered or not, according to the chosen criterion:

"q" is the threshold of indifference. It is the biggest value of "d" below which no difference between two actions is considered for the criterion.

"p" is the threshold of strict preference. It is the smallest value of "d" below which a strict preference between two actions is considered for the criterion.

"σ" is the equivalent parameter to the standard deviation of a Gaussian distribution.

According to the nature of each considered criterion, the adequate generalised criterion and its parameters must be chosen.

For example, a criterion with numerical value such as a criterion studying the local wind conditions by calculation of the relative standard deviation of the heights of buildings will correspond to the type V generalised criterion with a threshold of indifference equal to 0,1 and a threshold of strict preference equal to 0,25. This criterion must be minimized to ensure pedestrian comfort.

A criterion listing possibilities on a qualitative scale such as a criterion dealing with the inhabitants' participative mechanisms will correspond to the type 1 generalised criterion. With the highest level of good practice corresponding to the higher level of the listed possibilities, this criterion must be maximised. As soon as there is a qualitative difference between two actions, type I shows us that there is an absolute preference for the best solution.

4.4. Flows-criteria

As previously expressed, the number of criteria dealing with the conception of public places is raised. So the structuration, in particular sub-methods, generates the necessity of expressing the results of these as criteria for the global method. The proposition deals with the net preference flows stemming from particular methods as type III generalised criteria with "p" equal to 2. This choice of generalised criteria and the value of the threshold of strict preference protect the integrity of the data previously obtained inside the sub-methods.

5. WEIGHTS

The allocation of the weights relative to the diverse criteria is the most delicate step of the elaboration of a multicriteria method. It comes, a priori, as a subjective part in a process usually as objective as possible. It is why we will detail it with a lot of care.

The presented weights allocation technique is partially stem from the method of Delphi and partially from the Analytic Hierarchy Process of Saaty [3].

The postulate of the method of Delphi is that forecasts realized by a structured group of experts are generally more reliable than forecasts made by not structured groups or individuals. Concerning public spaces conception, these experts would either be town planners or sociologists or engineers for example.

This method consists in gathering the weights propositions that every isolated expert grants to every criterion. These propositions must always be justified. Then, having made them anonymous, a coordinator sends all the different propositions to every member of the group. A second tour takes place to let each member revises or not its weights propositions knowing the opinions emitted by the other experts. After a certain number of iterations, we generally observe a convergence of the values.

In spite of its good results, the long process of the Delphi technique handicaps this one. So, for the expression of the opinions and once they become enough converging at the eyes of the coordinator, we recommend to opt for a mechanism close to which Saaty elaborated. The proposed technique is presented below.

5.1. Votes

This phase is renewed with every voting iteration. For each possible pair of criteria XY, the questionnaire sent to each expert submits the question "what is the importance of the criterion X in regard to the criterion Y?". The possible answers correspond, for example, to a scale of nine possibilities as presented in table 2. Such a question with closer possible answers has for objective to avoid that the expert opts for a priori opened and motionless weights.

Table 2 : Example of possible answers

X having an overwhelming importance on Y	*X = 9Y*	*Y = 1/9X*
X considerably more important than Y	*X = 7Y*	*Y = 1/7X*
X much more important than Y	*X = 5Y*	*Y = 1/5X*
X moderately more important than Y	*X = 3Y*	*Y = 1/3X*
X being equal in Y	*Y = X*	
Y moderately more important than X	*X = 1/3Y*	*Y = 3X*
Y much more important than X	*X = 1/5Y*	*Y = 5X*
Y considerably more important than X	*X = 1/7Y*	*Y = 7X*
Y having an overwhelming importance on X	*X = 1/9Y*	*Y = 9X*

5.2. Convergence and treatment

Once there are enough converged opinions for the coordinator, the importance, or the preference of a criterion on another one, is calculated by geometrical average of the individual answers between these two criteria. The choice of geometrical and not arithmetical average is indispensable because the double direction of the scale of relative importance involves the application of multiplicative factors and quotients.

5.3. Checking matrix

On the basis of the geometrical averages considered by pair of criteria X/Y and their opposite corresponding to the preferences Y/X, a matrix is built for every method of the arborescence. This checking matrix synthetizes the importance of every criterion compared with the other criteria. Note that every criterion compared with itself obtains obviously the value 1.

Table 3 presents an example of checking matrix. This example is taken from an arborescence structuring the sub-methods in "sub-sub-methods". As part of the sub-method "Morphology", the considered sub-sub-method deals with physiological comfort considering dimensions and materials of the space.

Table 3: Example of a checking matrix

"/"	*Wind conditions*	*Day visual conditions*	*Night visual conditions*	*Acoustical conditions*
Wind conditions	*1*	*1*	*0,637*	*0,442*
Day visual conditions	*1*	*1*	*1,308*	*0,833*
Night visual conditions	*1,570*	*0,765*	*1*	*0,833*
Acoustical conditions	*2,265*	*1,201*	*1,201*	*1*

5.4. Relative weights

The process of Saaty uses complex calculations work out the weights of the criteria. The following approximation can be made.

At first, it is a question of calculating the geometrical average of each line of the checking matrix. This average illustrates the average preference of a criterion towards all the criteria with which it must be weighted. Secondly, we operate the sum of the obtained values. Finally, the quotients of the average preferences per their sum send back the relative weights of the different considered criteria. An example is presented in table 4 according to the data of table 3.

Table 4: Example of calculation of the relative weights

Criteria	Geometrical averages	Weights
Wind conditions	$(1*1*0{,}637*0{,}442)^{1/4}$ = 0,728	0,728/4,094 = 0,179
Day visual conditions	$(1*1*1{,}308*0{,}833)^{1/4}$ = 1,022	1,022/4,094 = 0,250
Night visual conditions	$(1{,}570*0{,}765*1*0{,}833)^{1/4}$ = 1	1/4,094 = 0,244
Acoustical conditions	$(2{,}265*1{,}201*0{,}833*1)^{1/4}$ = 1,344	1,344/4,094 = 0,327
Totals	4,094	1

The relative weights are exploitable both in an aggregative approach and in Prométhée multicriteria methods.

6. PRACTICAL RESULTS

Several actions can be put on the hot seat by a jury or a community during competitions or calls for tender between town planning and consulting firms. The necessity of a choice between several possible and many different actions can also in just a public or private office.

According to the objectives and needs of the studied public place, it is necessary to build the adequate multicriteria method and its benchmarking counterpart. When all the previously presented elaboration steps are realised, the possible actions can be studied and compared. According to our double approach, the practical results are double. They express firstly quality level then ranking between actions.

6.1. Benchmarking results

The benchmarking or distance to the optimum could be aggregated or not. A radar representation of all the studied criteria before aggregation permits an easy reading of the quality level of each criterion. Such radar is presented in figure 3. When all the studied criteria meet their optima, the disc is full.

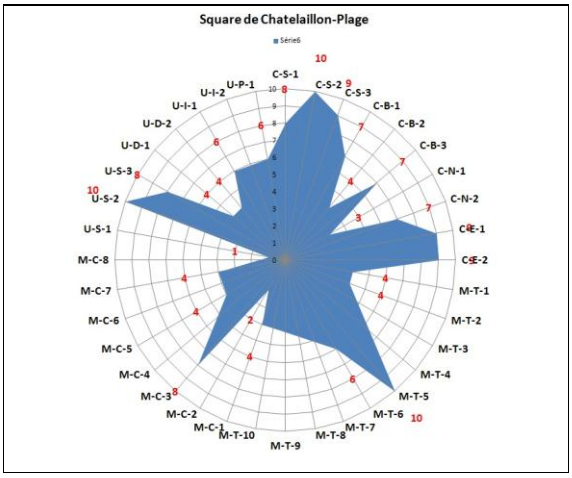

Figure 3: Example of non-aggregated benchmarking expression

When the criteria are weighted, the expression of benchmarking would be like the European energy labels or other qualitative or quantitative scale. In the European labels, the good practices receive an "A". Conversely, a very bad practice receives a "G". Intermediate situations receive an alphabetical value between these two limits. The whole expression of the aggregated benchmarking is contained in these only letters with no nuances.

6.2. Ranking results

According to the calculated net flows between actions, Prométhée II arranges totally them. According to the calculated ingoing and outgoing flows between actions, Prométhée I arranges them bringing to light potential incomparability. These two versions of Prométhée complement each other. Figure 4 present graphical expressions of the Prométhée rankings for six actions. Right-hand side is corresponding to the best actions.

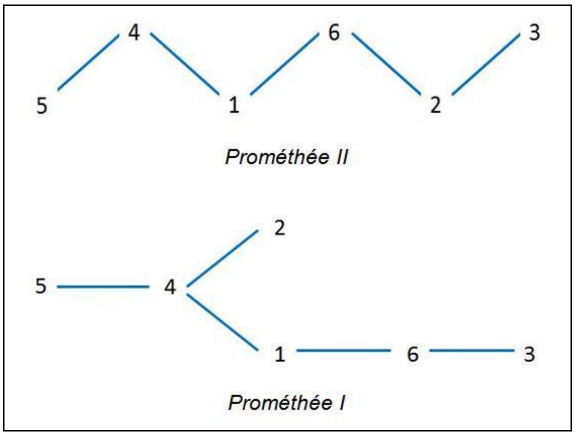

Figure 4 : Graphical expression of Prométhée I and II

Both results, benchmarking and Prométhée, bring to light the preference level and the quality of a solution compared to others without being simplistic in the treatment of the various factors.

7. SCIENTIFIC EXPECTATIONS

Large campaign of studies of real cases using a developed model allows adjusting this one. The data collected during such campaign would be treated with statistical tools like a matrix of correlation. This matrix would confirm or not the non-redundancy but especially the independence of the criteria. Still better, such statistical treatment could highlight unexpected links between constituent parameters of public spaces.

In addition, comparison between socio-psychological investigation and collected theoretical data would adjust a too theoretical approach not in touch with reality.

On the basis of the proposed methodology, the elaboration of such presented tools and its scientific validations are currently in progress according to the specifications of Belgian public spaces specificities.

8. CONCLUSION

Considering the quantity of different, and sometimes contradictory, data linked to the study of urban public spaces projects, the use of multicriteria decision-aiding tools is essential.

The use of such strategic tools allows passing beyond the highly rigorous compartmentalized visions of the various public or private stakeholders. These visions lead to decisions recovering from simple maxima and being often erroneous in a global approach. A contrario, a correctly built transversal multicriteria approach leads to solid decisions based on a right multidisciplinary compromise.

This paper presented a methodology for the elaboration of multicriteria tools dealing with both aggregative benchmarking and Prométhée methods. Both benchmarking and Prométhée results show us the preference level and the quality of possible solutions without being simplistic in the treatment of the various factors.

9. ACKNOWLEDGEMENTS

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Qualitative assessment of the urban public spaces by using the psychoacoustical parameters and semantic description

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Keywords: acoustics, soundscape, urban public places

Summary.

Nowadays, even by using the recently developed sophisticated acoustical and psychoacoustical measurable and quantifiable parameters, it still remains difficult to grasp the complete meaning of urban soundscapes. Acoustical evaluation of urban public places is often reduced to statistical analysis of the noise, which gives just a basic idea about the sonic environment. Development of a new method for the complex acoustical description and categorization of urban soundscapes is therefore necessary. Our research is done in the framework of the multidisciplinary project, which deals with the development and renovation of urban public places in Belgium. New method based on measurable acoustical and psychoacoustical parameters obtained from the so called "soundwalks", is combined with the semantic description of the given urban place. This method proposes the assessment of the soundscapes in three basic levels: First, the noise evaluation based on measurements followed by the well known statistical noise analysis; second, the qualitative assessment of the urban soundscape by using the psychoacoustical parameters and semantic description; and the third part dealing with the urban public place recognition based on acoustical information. This article focuses on the second part, e.g. the qualitative analysis, which is performed on the example of 20 streets in Leuven.

1. INTRODUCTION

Acoustics of the urban public places has to be understood more as a consequence or an aspect of the urban planning, rather than as an independent acoustical design. However this doesn't diminish the importance of this field. Acoustics, due to the surround character, i.e. sources doesn't have to be visible to hear them, might act as one of the best descriptors of the situation in the urban public places.

At the moment, generally accepted standard descriptors (parameters) of the acoustical quality in urban public places have not been defined yet and thus they are under the investigation in the framework of several projects on national and European level.[1,5,6,8,9]

Our research deals with four general research questions and research objectives defined as:

RQ1 : Which are the best acoustical descriptors for the urban public soundscapes? Descriptors have to be understood as (1) objective acoustical parameters (quantities) obtained from recording in situ given as a number and a unit (noise analysis is part of it), and (2) semantic categories for context-related sound (by using the subject-centred methods), which can't be described by numbers,

RQ 2 : Which clustering method is the most convenient in terms of categorisation of the urban public places?

RQ3 : The final decision about the criteria concerning the quality of public places after the combination of the acoustical and sociological data.

RQ4 : Understanding the correlation between the acoustical situation in the place and urban design leading to establishment of the acoustical prediction method for new designs or designs and renovations of urban public places.

This article deals with the first research question RO1, concerning the set of best descriptors for an urban public place

2. DEVELOPING THE METHODOLOGY

Our methodology is based on noise evaluation (NE) and qualitative assessment (QA). The noise evaluation is based on known noise maps and our own recordings in situ where the impact of noise on human health is the priority. The Qualitative assessment is about the human appreciation of the soundscape based on perception, evaluation and expectation. This part is based partially on “hard” data of binaural acoustical recordings followed by psychoacoustical analysis and on “soft” data with a respect to the context of the sound and human perception. As it is impossible to describe all acoustical aspects by numbers, we propose the description of the sonic environment also by words. Objective acoustical data are collected by using the soundwalk method[7] and the information about the human perception will be collected with cooperation with sociologist.

2.1 Noise evaluation

The noise evaluation is based on calculation of the statistical values such L_5 [dB], L_{10}, L_{50}, L_{95} [dB] as well as the equivalent noise level L_{Aeq} [dB]. This methods are well know and therefore, only little example is given in the figure 1.

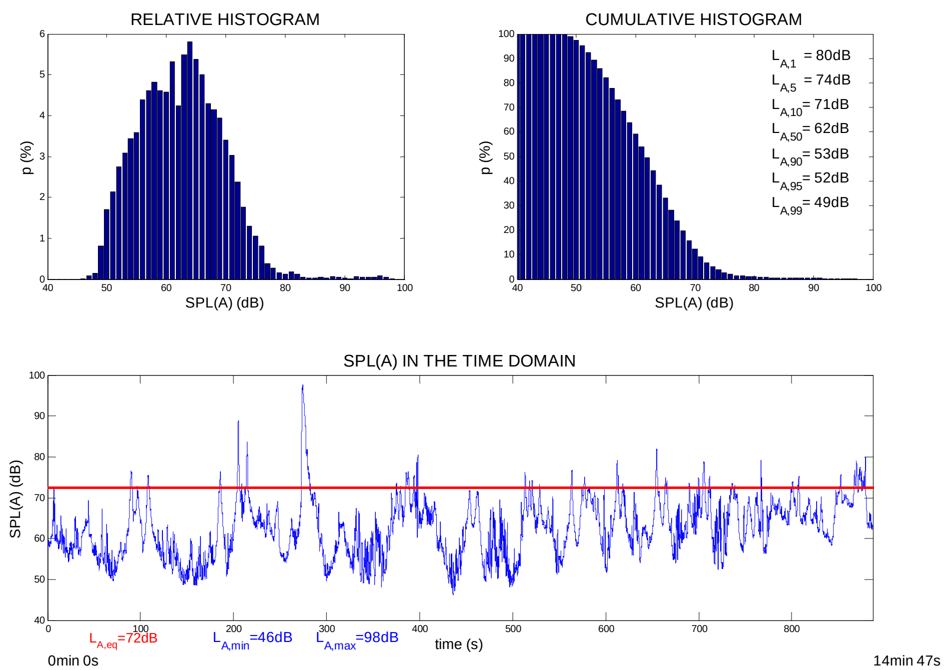

Fig. 1. Noise evaluation.

2.2 Qualitative assessment

The assessment of the acoustical quality in urban public place is in our methodology understood as psychoacoustical analysis, sound envelopment and semantic description. Our initial study of the behavior of the chosen psychoacoustical parameters, accompanied by sound level measurements, is based on 26 recordings (soundwalks), performed in the city of Leuven (in October 2007 - March 2008). The sound was recorded by using binaural in-ear microphones and a solid state recorder (M Audio Microtrack 24/94). All data were analyzed with 01dB Sonic software, in terms of the temporal evolution of the Sound Pressure Level L(A) [dB], Loudness N [son], Sharpness S [acum], Roughness R [cAsper] and Fluctuation Strength F [cVacil], followed by the calculation of statistical values (expressed as the value of the parameter (L, N, R, S or F) which was exceeded in x % of time during the recorded period.) The distribution of statistical values is different in case of each variable. Figure 1- left shows the statistical values of sharpness (S_1, S_2, …, S_{99}, S_{100}) based on 26 recordings of duration 10–15 minutes/per recording in several streets in Leuven. **Error! Reference source not found.** 1- right shows the statistical values of Roughness (R_1, R_2, …, R_{99}, R_{100}).

2.2.1 *Psychoacoustical analysis*

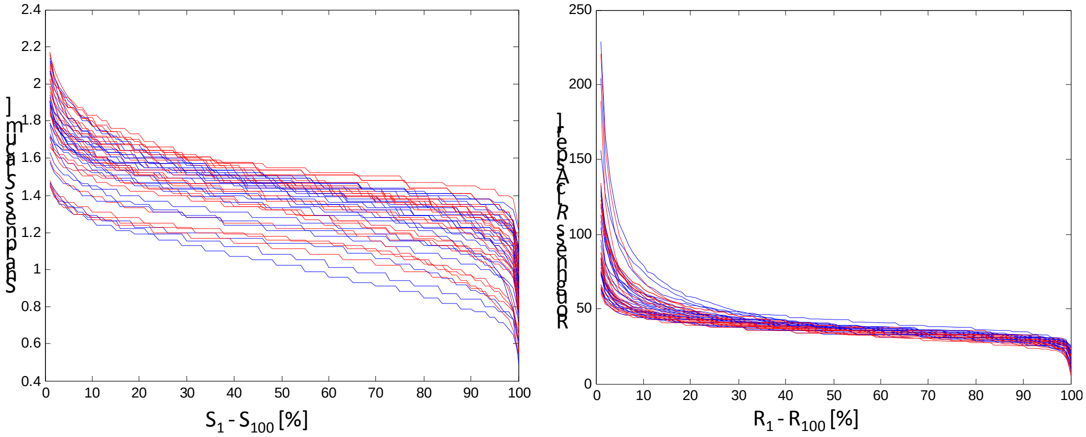

Fig. 1. Statistical values of sharpness and roughness values based of 50 recordings

To be able to decide about good descriptors, the maximum differences in soundscape within one place and the maximum differences between all the evaluated places concerning all chosen parameters have to be estimated and the character of the distribution has to be considered.

The global analysis of all measured places helps us to understand the behavior of the psychoacoustical parameters in the urban public places in particular. The background noise in the streets defined by L_{95} varies less from place to place than the peak values defined by L_5. We can conclude that it would not be very convenient to work only with average values L_{50}. On the other hand, statistical values of sharpness based on measurements in urban public spaces have rather normal distribution and so it seems acceptable to work only with average sharpness values S_{50} in the future. This has still to be confirmed by statistical analysis. The histograms of Loudness, Fluctuation strength and Roughness also confirm that the average values would not contribute as a sufficient quantity in the final set of descriptors.

2.2.2 *Sound envelopment*

Sound envelopment, defined by newly developed parameter urban interaural level difference proposed as “*uILD* number”:

$$uILD_1 = \frac{\sum_{i=1}^{n} \left(L_{Li} - L_{Ri} \right)}{n} \quad \text{[dB]} \qquad (1)$$

$$uILD_2 = \sum_{i=1}^{n} \sqrt{\frac{\left(L_{Li} - L_{Ri} \right)^2}{n}} \quad \text{[dB]} \qquad (2)$$

where L_{Li} is a value of the sound pressure level in the left channel in the time *i* and L_{Pi} is a value of the in the right channel in the time *i*. *n* is the number of the values.

In the analogy with *uILD* also the urban interaural roughness diference (*uIRD*), urban interaural sharpnes difference (*uISD*), etc. are calculated. The proposed parameter $uILD_1$ should show, which ear (left or right) was most of the time exposed to higher sound levels, sharpness values, etc. The $uILD_2$ gives an information about the surrounding of a person by sources in general and it is less sensitive on turning of the head during the recordings.

2.2.3 Semantic description

To express the context of the sound by numbers is not completely possible. In our research we therefore looked for a set of semantic categories, which could help in grasping the context of sound in evaluated soundscapes. We propose following categories:

1. Keynote Sounds, defined by Schaffer as soundsc which "may not always be heard consciously, but they outline the character of the people living there". Keynotes are created by nature or by permanently present sound sources. It is a kind of amorphous sound, in many cases sound perceived subconsciously as a background sound.
2. The Sound Signals, understood as foreground sounds, listened consciously, such a warning devices, bells, whistles, horns, sirens, etc. We can identify and localize these kinds of sound events.
3. The Soundmark, as a sound which is unique to an area. "Once a Soundmark has been identified, it deserves to be protected, for soundmarks make the acoustic life of a community unique" (Schafer).
4. The Rhythm. An urban area is determined by the rhythm of nature (changing day and night, or seasons in the year), but also by traffic jam events and quiet period or by trucks for garbage removal, etc. Some cities can be perceived slow and some fast.
5. The Harmony can be understood as overall acoustical comfort which depends on our acoustical expectation, such in the street with traffic lights we expect cars breaking and in the square with café's we will expect people talking while having a drink.

3. CONCLUSIONS

If we like to describe the urban public place from the qualitative point of view and not only quantitatively (e.g. what happens nowadays in noise analysis), deeper understanding of the urban sound is necessary. However, the deeper understanding of acoustical comfort can't be discovered only by an acoustician. Acoustical analysis is oriented on searching the best descriptors of the urban soundscape, but can't interpret the data without society response. Establishment of the recommended values of the acoustical parameters and proposing the criteria related to the perception and appreciation of the urban environments, is possible only after the interpretation of the acoustical numbers by psychological or sociological studies.

4. ACKNOWLEDGEMENTS

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Binaural Sound Source Localization in Real and Virtual Rooms*

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On the basis of a statistical evaluation of the binaural sound source localization performance during listening tests by human subjects, it is shown that the convolution of a measured head-related transfer function (HRTF) with the room impulse response generated by a hybrid image source model with a stochastic scattering process using secondary sources provides an adequate model for the prediction of binaural room impulse responses (BRIR) for directional sound localization in the frontal horizontal plane. The source localization performance for sound stimuli presented to test subjects in a natural way was compared to that presented via headphones. Listening via headphones tends to decrease the localization performance only, and only slightly when localizing narrow-band high-frequency stimuli. Binaural sound presented to test subjects via headphones was generated on the basis of measurements and simulations. Two different headphone conditions were evaluated. The overall localization performance for simulated headphone sound obtained using a simulated BRIR was found to be equivalent to the one using a measured BRIR. The study also confirms expectations that the deterioration of sound source localization performance in reverberant rooms is closely linked to the direct-to-reverberant ratio for given loudspeaker and listener positions, rather than to the reverberation time of the room as such.

0 INTRODUCTION

In recent years intensive research has resulted in the development and implementation of powerful noise suppression algorithms in modern digital auditory prostheses—hearing aids (HA) and cochlear implants (CI). Good results have been obtained by different approaches, using multiple-microphone adaptive filter techniques that rely on spectral as well as spatial information [1]–[4]. However, these techniques are typically developed and evaluated in monaural systems. These modern adaptive signal processing approaches are not optimized for the preservation of interaural information when used bilaterally. A correct presentation of interaural differences (in amplitude and time) is a prerequisite for localizing sound sources and for improved speech understanding in noise due to the spatial release from masking and is often not taken into account. Many of the speech processing algorithms often work well in laboratory conditions and in rooms with short reverberation times, but in real-life acoustical situations they may strikingly fail.

Most studies focus on monaural speech understanding issues in different acoustical environments [6]–[8]. At present different studies are being carried out toward modeling binaural speech intelligibility. Different speech intelligibility models based on a combination of the equalization–cancellation model with binaural extensions of the speech intelligibility index or the speech transmission index are nowadays enhanced to incorporate binaural listening situations under various conditions [9], [10]. In this research measured and simulated conditions are used.

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Listening tests were made with both normal and hearing-impaired subjects. Although simulation software (such as ODEON® [11]) has often been used to model acoustical environments, a perceptual validation for speech intelligibility purposes was done only very recently [12]. Furthermore no in-depth validation of simulation software has ever been carried out in terms of predicting the impact of the virtual acoustical environment on directional hearing or the localization of sound. In our research we are dealing with this important aspect of the virtual models of rooms.

Recent studies have shown that signal processing algorithms for noise reduction and compression, as implemented in modern commercial hearing aids, can lead to distortions and have a large impact on the localization performance of hearing-aid users [13]–[15]. This illustrates the need to validate signal processing algorithms with respect to their preservation of binaural cues and spatial awareness.

Performing perceptual evaluations with normal-hearing and hearing-impaired subjects using sound localization test setups in different rooms with different acoustical properties (such as churches, anechoic rooms, restaurants, halls, or railway stations) is very laborious and time-consuming, and therefore very difficult to realize in practice. Virtual acoustics may be very useful for the evaluation and development of signal processing strategies for auditory prostheses. However, the question remains to what extent these virtual acoustic techniques result in an accurate prediction of real-life performance of the different algorithms.

Different methods have been used in the past to create virtual auditory environments. Two approaches are envisaged to reproduce real-life acoustical environments: 1) the presentation through multiple-loudspeaker arrays of multichannel recordings, and 2) acoustical modeling of real rooms (listening environments) combined with binaural presentation to the listener via headphones or direct audio inputs.

While such systems may generate perceptions of spatial hearing successfully, it is not straightforward to satisfy the quite stringent accuracy requirements concerning binaural cues. The interaural time difference (ITD) and the interaural level difference (ILD) have to be reproduced accurately enough for correct spatial hearing.

A virtual auditory space can be synthesized using a so-called crosstalk cancellation system [16]–[22]. Crosstalk cancellation systems use digital filters based on measured head-related impulse responses (HRIRs). The generation of the final cancellation is based on these HRIRs. However, several research studies have revealed some limitations of this technique. Several authors [23]–[25] have shown that many of the systems introduce front–back confusions, in particular if only two loudspeakers are used, and large errors appeared close to the target positions at $\pm 90°$. Several studies also investigated the binaural performance of a multiple-loudspeaker system [22], [26]. With these binaural crosstalk systems difficulties have been reported in delivering accurate ITD and ILD cues.

Another approach for recreating the spatial soundscape with multichannel loudspeaker setups is the spatial impulse response rendering method. It has been shown to be successful to some degree in creating virtual acoustical environments [27], [28]. A major drawback of most of these methods is that they have not (or only in a minor way) been evaluated and validated perceptually. The latter has to focus on directional hearing (sound localization) and speech understanding (spatial unmasking), which are of extreme importance in the daily lives of both normal and impaired-hearing listeners.

Other possibilities of acoustical reconstruction of real-life auditory situations in laboratory or clinical conditions are through headphone listening tests. These experiments can be based on binaural impulse response measurements in situ, such as using an artificial head, or by advanced acoustic modeling of a room in prediction software [14], [29]. The latter represents a very flexible approach for preparing listening tests in terms of easily replacing HRTFs (individual or artificial head) and in terms of swiftly changing the acoustics of a virtual room without having to measure impulse responses in this room. HRTFs represent the impulse response of an incoming quasi-plane wave as a function of the azimuthal and sagittal angle of the wave vector in the axially symmetric coordinate frame of the head [30], [31].

The process of rendering the audible information from an acoustical room simulation to achieve a virtual three-dimensional sound of a given space is generally known as auralization. Virtual acoustics combines the properties of the sound source (directivity and power spectrum), the listener (HRTF), and the room (BRIR) to generate audible information (such as auralized sound). The first auralization attempts were monaural and probably date from the era of the first experiments with frequency-transformed music signals. These were played in a scale model by Spandöck in 1934 [32]. It seems that the first computer-based auralization experiments were done in the 1960s by Schröder et al. [33] and in the late 1970s by Allen and Berkley [34]. Binaural auralization was introduced a decade later in the work of Pösselt [35], then followed by many others [36]–[38]. Extensive work on binaural room simulation and scale acoustics models related to spatial hearing was also done by Blauert and coworkers [39], [40]. In general, virtual modeling of binaural signals in a room is based on convolving anechoic sound samples with the simulated BRIR and with the transfer function of the loudspeaker. The BRIR simulation can be obtained in several ways by wave-based or ray-propagation methods. The main wave-based approaches are the finite-element method and the boundary-element method, and ray-propagation methods are based on ray-tracing, cone-tracing, or image-source models [34], [41], [42].

Wave models are based on solving the wave equations on a three-dimensional grid defined by the user. These models can give accurate results at a single frequency. However, the calculation time is often too long for practical purposes, since a minimum of six elements per wavelength is necessary to obtain reliable results. Moreover the number of natural modes in a room increases with the third power of the frequency, and a deterministic approach becomes redundant, certainly above the limit frequency, as was pointed out by Schröder [43] in the 1950s already. Therefore in practical applications finite-element methods are used only for the simulation of very small and simple rooms and/or for the lower frequency range. In architectural acoustics, geometrical methods based on sound propagation along rays are used much more often. These methods usually give reliable results in the high- and middle-frequency range, and their calculation times are significantly shorter than any of the wave-based programs [44].

A hybrid calculation method based on the combination of the image source method (ISM) and an adapted ray-tracing method is very popular in architectural acoustics and has provided a good and useful tool for assessing the acoustical quality of a room during architectural design [45], [46]. Some work was done on the effects of reverberation in room models on localization [47] as well as on the estimation of localization errors introduced by room reflections [48]–[50]. However, research on validating the suitability of these acoustical models according to sound localization and speech perception for applications in the development and evaluation of new sound processing strategies for auditory prostheses, is nonexisting, or at least very limited. Therefore this study aims at validating the hybrid calculation method by verifying that binaural signals, generated by this method, which involves both a predicted room impulse response and a measured or simulated HRTF, can be used to recreate sound localization cues accurately for a listener in a virtual environment. Although a final judgment about the global auralization quality comprises testing of the accuracy of sound localization for azimuth and elevation angles, that is, testing the front–back confusion when nonindividualized HRTFs are used as well as externalization and overall spectral quality, this paper deals with localization in the frontal horizontal plane, and thus the preservation of binaural ITD and ILD cues, which are addressed in this study, because together with speech reception they are the most relevant for listeners in daily life. For the validation, a special acoustical environment, namely, the standardized reverberant room, was chosen. Normal-hearing subjects participated in the perception tests.

The global research question of this study can be formulated in the following questions:

1) What is the difference in localization performance when localizing sound sources naturally and when using headphones? This question comes prior to the other research questions, since ultimate testing of the global simulation tool involves comparing the associated localization performance with the natural situation where listeners do not use headphones.

2) What is the difference in localization performance when using headphones and generating stimuli with measured impulse responses or with virtual acoustics software? This issue is closely related to the accuracy of the hybrid simulation method to predict a BRIR.

3) How does reverberation affect the localization of sound sources in general? [51], [52].

All research questions are answered in detail, including a differentiation in terms of the frequency contents of the stimuli used. This frequency-dependent analysis helps to distinguish the impact of the different parameters on the binaural cues, as it is well known that the ITD and ILD cues are dominant at low and high frequencies, respectively [53]–[56]. In practice three different stimuli were used in the experiments: a) high-frequency noise centered around 3150 Hz, b) low-frequency sound in the 500-Hz one-third-octave band, and c) the rather broad-band sound of a ringing telephone, which also contains a lot of transient information. For questions 1) and 2) the influence of the distance between loudspeaker and listener, which determines the direct-to-reverberant sound level difference, is also investigated [57]. The third question is addressed by comparing the results from listening tests performed in the reverberant room with those in anechoic conditions. In an anechoic environment only direct sound reaches the head. In real life the environment is such that the sound waves emitted by the source are reflected from different objects or room surfaces, resulting in late reflected wave arrivals from all directions. Therefore it may be expected that reverberation decreases our ability for directional localization, that is, the ILD is very sensitive to standing waves in a room, whereas the ITD quality deteriorates due to the presence of multiple noncoherent reflections. However, as we know from our personal experience, even in very reverberant situations our ability to localize sound is not completely lost. The influence of reverberation should thus be analyzed carefully.

In Section 1 the procedures used to obtain the HRTF of the artificial head, and the determination of the BRIR of the reverberant room are elaborated. Their implementation for listening tests is described. The localization performance of the listening subjects in different scenarios is statistically analyzed in Section 2 and discussed in Section 3. Conclusions are given in Section 4.

1 METHODS

1.1 HRTF and BRIR Measurements

HRTF measurements on a CORTEX® MK2 manikin artificial head were performed in an anechoic room. The artificial head was placed in the middle of a ring of 2.0-m inner diameter. Thirteen single-cone loudspeakers (FOSTEX® 6301B) of 10-cm diameter were placed every 15° in the frontal plane. A two-channel sound card (VX POCKET 440 DIGIGRAM®) and DIRAC 3.1 software type 7841 (Bruel and Kjaer sound and vibration measurement systems) were used to determine, for every angle, the impulse responses for the left and right ears by transmitting a logarithmic frequency sweep. Deconvolution of the frequency response of the loudspeaker was not necessary, since for the frequency range of interest (200 Hz to 10 kHz) it was essentially flat (-3 dB points of amplifier response at 20 Hz and 50 kHz). The HRTFs for the left and right ears were determined in the standard way, by calculating the inverse Fourier transform of the spectrum of the respective recorded sound normalized by the transmitted sweep spectrum (obtained via a hardware loopback calibration procedure).

These measurements were later used for the creation of sound samples for the listening test in anechoic conditions, by convolving measured dry binaural impulse responses with the three chosen stimuli. The measured HRTF information was also prepared in a plug-in format to be read by the ODEON® software to calculate the BRIRs, which are used to generate the stimuli of the reverberant environment, that is, to produce the auralization. Since binaural effects in the sagittal plane were not of interest for this research, which is dedicated to localization in the horizontal plane, regardless of the sagittal angle of an incoming ray, a value of 0° (horizontal plane) was assumed for the HRTF. This is equivalent to the assumption that the influence of the sagittal direction on the HRTF is small and independent of the azimuthal dependence.

In the reverberant room, measurements of binaural impulse responses (with the same artificial head as in the anechoic room) were done for the same loudspeaker–receiver setup as in the anechoic room [Fig. 1(a)], that is, for loudspeakers at 1-m distance from the head. In addition, to investigate the localization of a sound source at greater distances in a reverberant sound field, loudspeakers were put on stands and placed at a 2.4-m distance from the artificial head [Fig. 1(b)]. The 13 measured impulse responses from both experiments were then convolved with anechoic sound samples of the three stimuli for the listening tests with headphones.

Also the impulse response of the headphones placed on the artificial head and recorded via its in-ear microphones was measured using the same sound card and software as for the HRTF characterization described. This transfer function was deconvolved from the sound samples used for the listening tests, thus avoiding an unwanted accumulation of the effect of the transfer function of the ear canal of the artificial head (via the HRTF recording) and that of the ear canal of the listener during the headphone test.

1.2 BRIR Simulations

ODEON® software v.9.0 was used for the room acoustical simulations. This software uses a hybrid algorithm where two geometrical methods are combined to predict the impulse response of a virtual room. The simulation of the room impulse response (RIR) is in principle performed in two steps. The first part, which contains information about early reflections, is calculated by combining the image source method and early scattered rays. The duration of the early part can be chosen by the user via the so-called transition order (TO). This is the maximum number of image sources taken into account per initial ray [58]. The second part of the RIR, the late reflections, is calculated by a modified ray-tracing algorithm that also takes into account the scattering coefficient of the involved surfaces. At every reflection event, local diffuse secondary

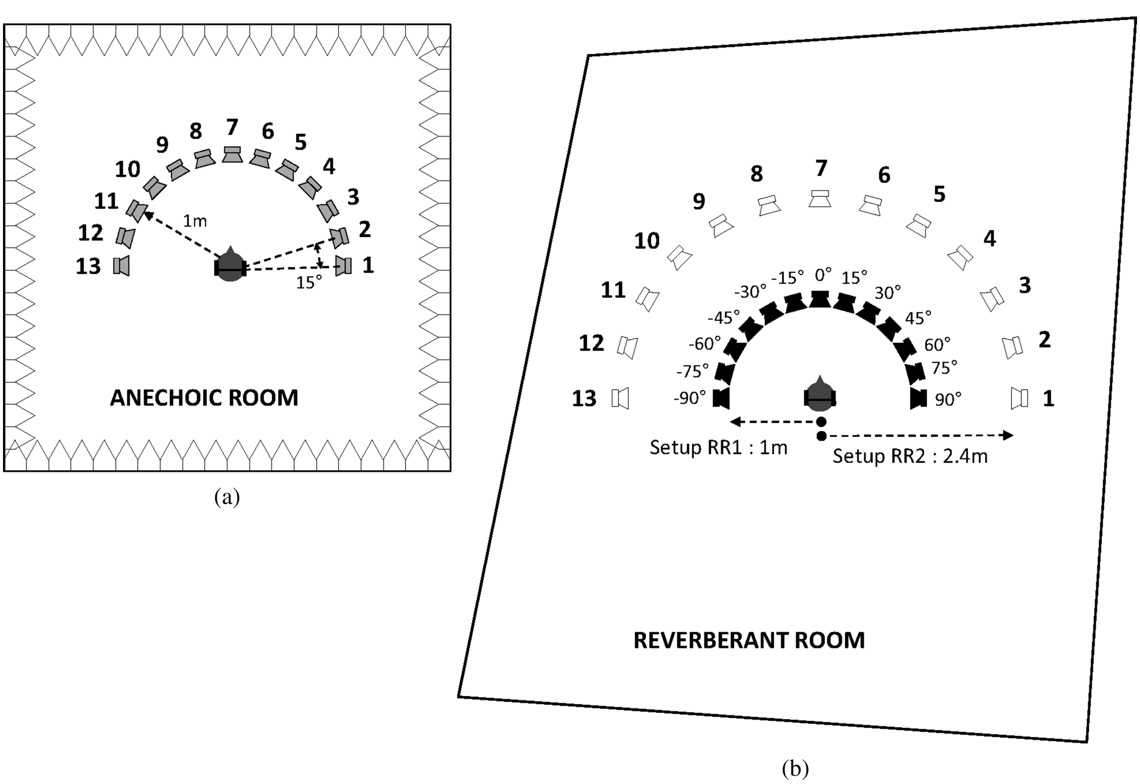

Fig. 1. (a) Setup in anechoic room. (b) Setup in reverberant room. An array of 13 loudspeakers is positioned in the frontal horizontal hemisphere of the subject or manikin. The loudspeakers are placed at 1 m of the subject. In the reverberant room a second array of loudspeakers is used with a radius of 2.4 m. In all setups the impulse responses between loudspeakers and a CORTEX MK2 manikin are measured. These impulse responses are used to generate stimuli, which are presented over headphones. The impulse responses measured in the anechoic room are also used in ODEON® to generate a second set of headphone stimuli.

sources are generated, which radiate sound with a directivity according to Lambert's cosine law [59], [60].

This combined approach is quite popular because the image source method (ISM) captures early reflections very accurately, but it is too computationally intensive to calculate all of them for later reflections, so statistical ray tracing is good enough to capture the tail. The hybrid approach has been validated for room acoustics use by Vorländer and Bork [61], [62] in a number of round robin studies.

The ISM is based on the principle that a wave front arriving from a point source and reflecting from an infinite plane can be drawn as if it were originating from an image source. That image source can be evoked as a mirror source, considering the reflecting plane in the model as a mirror plane for the incident ray. Also secondary image sources of the initial image sources can be introduced, and reflections of the second order, third order, and so on, can be calculated. The more surfaces the acoustical model of the room contains, the more image sources have to be constructed. Obviously, for computational reasons the exclusive usage of the ISM is suitable only for smaller rooms with not too complicated a geometry [34] and not too much reverberation. In practice, as mentioned before, hybrid methods, combining ISM with RTM, are often used.

In the ray tracing method (RTM) a large number of rays are sent from a point source in a large number of directions, according to the user-defined directivity of the loudspeaker or sound source. The trajectory of each ray is determined by its reflection from the boundary surfaces according to Snell's law. The intensity I of a ray decreases with the travel distance according to the classical geometrical attenuation of a point source ($I \sim r^{-2}$) and is reduced at every reflection according to the absorption coefficient (defined per octave band) of the incident surface. Scattering of sound is introduced in the computer model via the scattering coefficient δ [%], which is defined as the ratio of the sound energy reflected in nonspecular reflections to the total reflected sound energy [59].

The detailed algorithm of the ODEON® software has been described by their developers [63], [64]. Essentially, ODEON® software calculates the BRIR by transmitting stochastically generated rays from the source that arrive via direct sound or via one or multiple reflections, taking into account appropriate geometrical rules, at the receiver point. (In the present case this point is located exactly between both ears). The binaural impulse responses are calculated as follows. First the impulse response is determined for each ray individually when the listener is absent, taking account of the directivity of the sound source and the spectral attenuation of the reflection surfaces encountered on the path from the sound source to the location of the center of the listener's head. Then the left-ear and right-ear HRTFs are used to account for the influence of the listener's head on the incident sound, using the HRTFs corresponding to the direction of the incoming ray (Fig. 2). Finally the responses for the individual rays are summed. The HRTFs used can be input by the user, and therefore can be either based on measurements on a real subject or an artificial head [30], or computed by a numerical method such as the boundary-element method

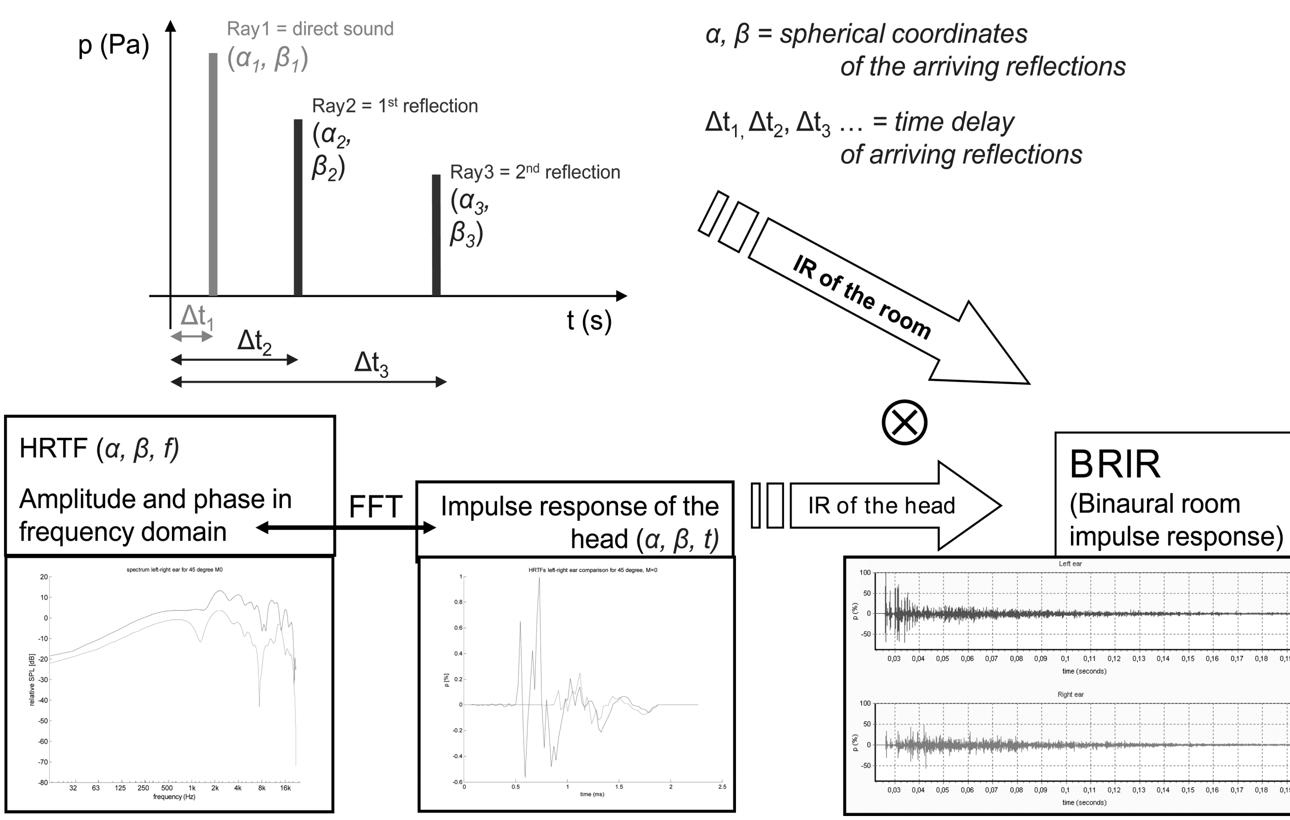

Fig. 2. Illustration of BRIR calculation.

[65]. A geometrical computer model of the reverberant room (Fig. 3), which has a volume $V = 198\ \text{m}^3$, was based on the measured dimensions. The reverberation time T_{30} [s] of the room was experimentally determined following ISO 3382 by using an omnidirectional point source (B&K 4295) and an omnidirectional microphone (B&K 2642) (Fig. 4). During the measurements, equipment (such as the 13 loudspeakers) and one test subject were kept in the room in order to approach the acoustical circumstances of the listening tests. Based on this in situ measurement the acoustical model was calibrated [66].

The loudspeakers (FOSTEX® 6301B) were simulated with the proper directivity and spectrum, as measured in an anechoic room. The impulse response was determined from the signal recorded by a B&K 2642 microphone at 1 m from the loudspeaker using the DIRAC procedure mentioned and the Digigram VXPOCKET soundcard and varying the loudspeaker–microphone azimuth angle in steps of 5°. In ODEON® the loudspeaker directivity is introduced by assigning to every stochastically transmitted ray an amplitude that is related to the respective azimutal and elevation angle with respect to the normal to

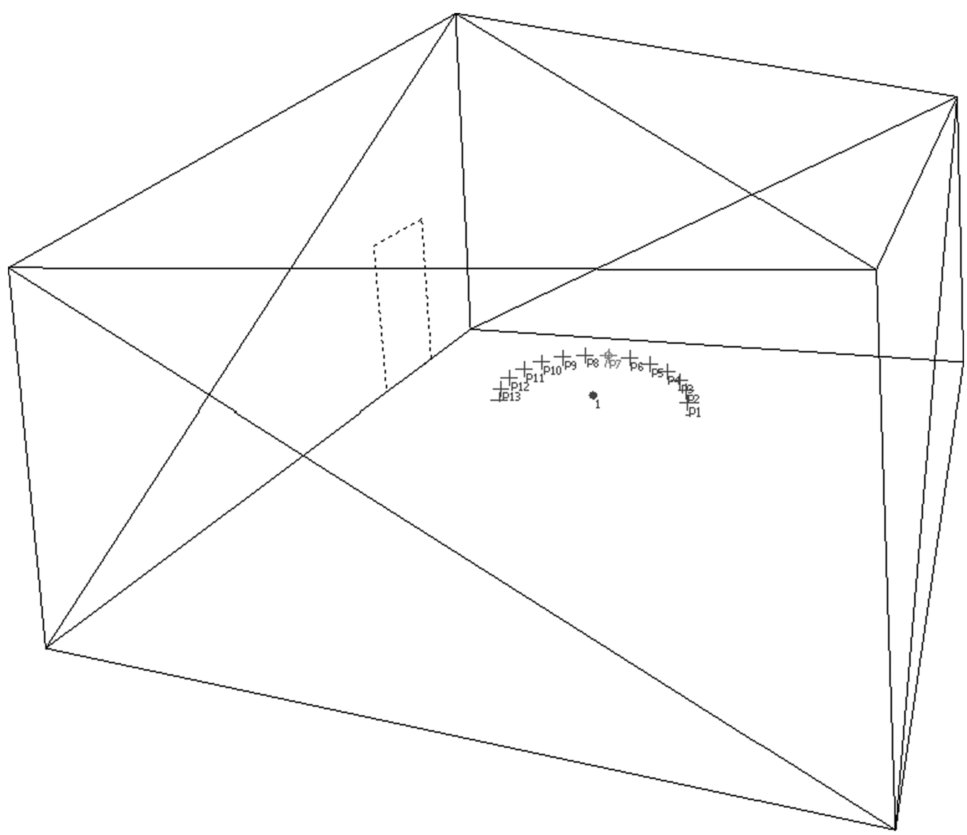

Fig. 3. Geometrical model of reverberant room in ODEON® software.

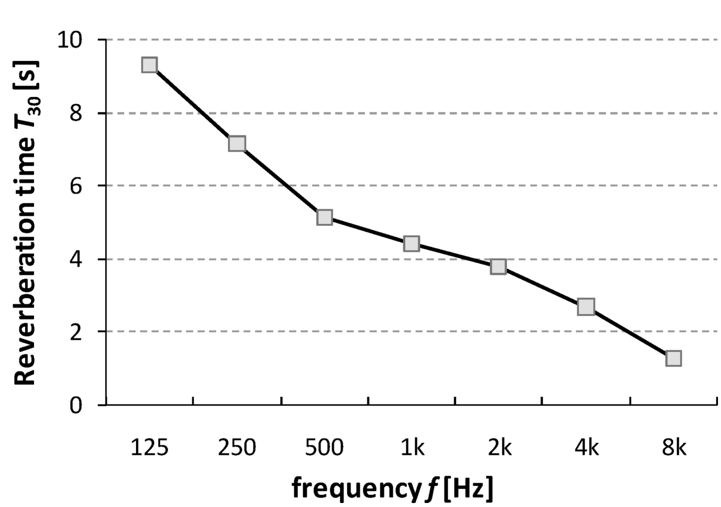

Fig. 4. Reverberation time T_{30} as measured in reverberant room according to ISO 3382 (2004).

the loudspeaker surface. The receiver properties were defined by the measured HRTF of the artificial head. The simulation was performed with 6000 rays, a maximum reflection order of 2000, and a transition order TO = 2, that is, the image source method was used to calculate the first- and second-order reflections. The rest of the RIR was calculated using the special ray-tracing method. The influence of the TO value on localization perception tests was investigated in [67].

1.3 Stimuli

To investigate the two binaural cues, ITD and ILD, separately, three different stimuli were presented in the listening tests. As mentioned earlier, for low frequencies (<1 kHz) the localization mechanism of a human is dominated by ITD information, whereas for frequencies above 1.5 kHz the ILD cue is dominant for directional interpretation [53]–[56].

To obtain an idea about ITD-based recognition, one-third-octave band noise with central frequency f_c = 500 Hz and a duration of 200 ms was chosen. Investigation of ILD interpretation was done with a one-third-octave band of the same duration (200 ms) and a central frequency f_c = 3150 Hz. Although 3150 Hz might be considered more upper middle frequency than really high, thus only just above the region of hair cell phase locking, it is well above 1500 Hz. Our choice of 3150-Hz sound was guided by a global project goal, which was to test hearing-impaired persons who often suffer from a cut in auditory sensitivity of high frequencies. The third stimulus was a sound of a broad-band telephone ring with a duration of 1 s which contains both low- and high-frequency components as well as transient information, and thus was expected to be easier to localize. In order to keep the perception of the telephone sound familiar to the listening subjects, the length of the telephone signal was not shortened to 200 ms.

All sound signals were cosine windowed with rise and fall times of 50 ms. The stimuli in all listening tests were presented at 68 dB(A) (equivalent sound pressure level $L_{A,eq}$ over the duration of the window). A roving level [13] of 4 dB was applied in tests both with and without headphones, that is, after equalizing the left and right sound pressure levels, they were increased equally with random variations of between 0 and 4 dB during the listening test. This procedure allowed listeners to use only ITD and ILD cues, since the sound level of stimuli played from one particular loudspeaker was heard on different sound levels (up to 4 dB difference). This made it impossible for the listening subject to distinguish loudspeakers on the basis of how loud they sound. If the same stimulus were repeated without several roving level adjustments, the subjects would associate the sound level on which the stimulus was presented with its direction due to the acoustical shadow over the contralateral ear, which is dependent on the angle of incidence. The brain stem would receive an extra, monaural cue to localize sound. In a real-life situation the absolute level of sound is often unknown, making tests without roving level adjustment not representative.

1.4 Subjects

Seven normal-hearing subjects of between 24 and 50 years participated in the experiments. They had maximum hearing thresholds of 15 dB HL measured at all octave frequencies from 125 Hz to 8 kHz.

1.5 Setup and Listening Tests

Listening tests were carried out in both the anechoic and the reverberant room. The tests were designed in the framework of the research questions mentioned in the Introduction. Both rooms were well insulated from outdoor noise, with background noise levels not exceeding 30 dB(A). Since the main focus of the research was to investigate the localization ability by using binaural cues, experiments were restricted to the frontal horizontal plane only. Tests of front–back confusion, which relates to monaural spectral cues, were not performed, since this would only complicate the data analysis.

1.5.1 Anechoic Room

For tests in the anechoic room, subjects were seated in the middle of a ring with 13 loudspeakers (labeled 1–13) located in the frontal horizontal plane every 15° between the azimuth angles −90° and +90° at a distance of 1 m. The subjects' ears were at the height of the loudspeakers, which were 1.2 m above the floor.

Two listening scenarios were implemented.

1) Sound samples were played from loudspeakers via a multichannel soundcard. The listening subject had to identify the loudspeaker in the free field by his or her own ears (OE).

2) Sound samples based on measured anechoic binaural signals were played from SENNHEISER® HD650 headphones, and the listening subject was asked to identify the virtual loudspeaker (HPM).

1.5.2 Reverberant Room

Listening scenarios in the reverberant room were created for the real and the simulated reverberant room. In both cases the listening subjects were sitting in the real reverberant room, identifying the sound emitting loudspeaker:

1) In situ by his or her own ears (OE)

2) Via headphones based on measurements of HRTFs obtained with the artificial head in the reverberant room (HPM)

3) Via headphones based on the ODEON simulation with the task to identify the virtual loudspeakers in the simulated reverberant room (HPS).

In the environment of the reverberant room, two setups were built (see Fig. 1). In setup RR1 the loudspeakers were placed on a ring with inner radius 1 m. In setup RR2 the loudspeakers were located on a ring at 2.4 m from the listener's head. This was the maximum possible distance in our reverberant room while keeping the distance between loudspeakers and walls larger than or equal to 1 m. The two scenarios represent a situation with a good and one with a poor direct-to-reverberant sound level difference. As a quantity expressing the direct-to-reverberant ratio we chose.

$$C_{DR} = 10 \log \frac{\int_0^{t_{DR}} p^2(t)\ dt}{\int_{t_{DR}}^{\infty} p^2(t)\ dt} \quad [\mathrm{dB}] \tag{1}$$

where t_{DR} is the early time limit (separating direct and reverberant sounds) and p is the sound pressure. We calculate C_{DR} from the impulse responses measured by the artificial head in the reverberant room placed at, respectively, 1 m and 2.4 m from the source. Due to the shadowing of the artificial head and the directivity of the loudspeakers (more directive at higher frequencies), C_{DR} varies with the angle of the arriving sound and increases with frequency. In setup RR1 the values for C_{DR} are between -12 and -2 dB around 500 Hz and between -12 and 8 dB around 3 kHz. For setup RR2, due to the larger loudspeaker–listener distance and, consequently, the lower direct sound level, the values were lower. C_{DR} varies between -17 and -12 dB around 500 Hz and between -18 and -1 dB for 3 kHz. The negative values of C_{DR} for all angles and both frequencies in setup RR2 indicate that the direct sound is weaker than the reverberant sound.

1.5.3 Listening Tests

In all listening tests the task of the subject was to identify one of the 13 loudspeakers (or an apparent sound source, that is, a virtual loudspeaker in case of the headphone tests) from which the sound was heard, or the most likely loudspeaker if sound was recognized, for example, between two loudspeakers. All answers were reported by the listening subject to the operator via a microphone communication system by announcing the number of the sound source from which the sound was heard. Each subject was asked to continuously keep his/her head pointed toward the central loudspeaker (speaker 7 at 0° in Fig. 1) and was observed by the operator sitting in the next room by using a webcam. Sound samples were played randomly with three repetitions of each loudspeaker in every test. One test therefore consisted of $3 \times 13 = 39$ stimulus presentations or localization tasks. Sufficient time was kept between two tasks in order to allow the sound of a previous task to decay sufficiently before presenting the next sound. The presentation of the signals and logging of the answers were controlled by an operator, who controlled the homemade control and data-collection program from outside the listening room while having remote acoustic and webcam contact with the listening subject. For the sake of supplying visual association in the headphone tests (HPM and HPS), the subjects sat in the same position in the room as in the OE experiment, that is, in the presence of thirteen (inactive) real loudspeakers. The level of the stimuli in all headphone listening tests was calibrated to 68 dB(A) by means of an artificial ear (B&K® type 4152). Every subject participated in the same test twice (test and retest) on two different days, in order to assess the reproducibility of his or her answers. One listening test session took about 45 min in anechoic and 90 min in reverberant conditions, including one or two breaks. A summary of all performed listening tests is presented in Table 1.

In the statistical analysis of the results the root-mean-squared (rms) error in degrees is used:

$$\mathrm{rms}[°] = \sqrt{\frac{\sum_{i=1}^{n} (\Theta_{\mathrm{response,i}} - \Theta_{\mathrm{true,i}})^2}{n}} \tag{2}$$

where $\Theta_{\mathrm{response}}$ and Θ_{true} are the recognized and the true azimuthal angle, respectively, and n is the number of stimuli presented. In the calculation of the rms value large errors have a larger impact than small ones. When analyzing the rms error, the listening subject could choose from only thirteen fixed loudspeaker positions. As a result the smallest error per answer was the distance between two neighboring loudspeakers, that is, 15°. The smallest nonzero error during one test, in which each of the thirteen loudspeakers was repeated three times, was 2.4° rms.

2 RESULTS AND ANALYSIS

Tables 2–4 contain the individual and averaged localization results of the seven normal-hearing subjects in the different test conditions (see also Fig. 5). The average values of the test and retest conditions are given since no significant differences between both tests were observed. All the data are analyzed using SPSS 15.0. For conciseness, in the following, the term "factorial repeated measures ANOVA" is abbreviated to "ANOVA." All reported

Table 1. Summary of all listening tests.[a]

	Anechoic Room						Reverberant Room																	
Listening Scenarios	Setup AR						Setup RR1									Setup RR2								
	OE			HPM			OE			HPM			HPS			OE			HPM			HPS		
Stimuli	500 Hz	3150 Hz	Telephone	500 Hz	3150 Hz	Telephone	500 Hz	3150 Hz	Telephone	500 Hz	3150 Hz	Telephone	500 Hz	3150 Hz	Telephone	500 Hz	3150 Hz	Telephone	500 Hz	3150 Hz	Telephone	500 Hz	3150 Hz	Telephone

[a] Setup AR—anechoic room; setup RR1—reverberant room where distance between loudspeakers and receiver was 1 m; setup RR2—reverberant room where distance between loudspeakers and receiver was 2.4 m.

pairwise comparisons are Bonferroni corrected for multiple comparisons. The reported p values are lower bound values, and a significance level of $p = 0.05$ is used throughout this paper. First a short overview of the data is given. Later the ANOVAs used to examine the research questions are presented.

In Tables 2–4 it is observed that the high-frequency stimulus is localized least accurately. The broad-band telephone stimulus is localized best, and the data of the 500-Hz noise band approach the data of the telephone signal. Moreover it is observed that the range of responses, especially those of the anechoic data, corresponds very well with normal-hearing data [13]. A second observation is that the localization accuracy of the normal-hearing subjects is not drastically influenced by reverberation, nor by how the stimuli are generated or presented to the subjects. This motivates the use of measured or ODEON® generated impulse responses during the first evaluation stages of an algorithm. Statistical analyses are performed to evaluate the data thoroughly. In the first analysis the difference between natural localization and performing headphone experiments with recorded impulse responses using a CORTEX MK2 manikin is examined. In the second analysis the localization performance when using recorded impulse responses is compared to the condition in which impulse responses are generated by ODEON®.

Table 2. Individual and average rms data (°) of normal-hearing subjects for different test conditions.[a]

	500 Hz		3150 Hz		Telephone	
Rms Error (°)	OE	HPM	OE	HPM	OE	HPM
S1	12.9	12.9	19.3	17.9	8.0	6.8
S2	10.6	9.5	16.7	22.6	6.4	6.8
S3	12.1	10.8	17.0	21.8	6.6	9.9
S4	8.2	8.8	13.9	16.6	6.2	7.0
S5	8.4	14.8	16.0	20.7	7.2	9.8
S6	15.2	14.6	18.8	23.6	10.3	10.9
S7	9.0	8.3	18.9	24.7	6.8	3.3
Average	10.9	11.4	17.2	21.1	7.3	7.8
Standard deviation	2.6	2.7	1.9	2.9	1.4	2.6

[a]Tests are done in an anechoic room with a distance between loudspeakers and subject of 1 m (AR).

2.1 Natural Localization versus Measurements (CORTEX MK2 Manikin)

An important question in this paper is whether using impulse responses measured in an acoustic environment with a CORTEX MK2 manikin has a large influence on localization performance. This is evaluated by examining the own-ear data and the HPM data gathered in the three different acoustic settings, abbreviated as setups AR, RR1, and RR2. The natural localization data, also referred to as own-ear data (OE), and the data of the measured impulse responses (HPM) are inserted in an ANOVA using the following main factors:

- Stimulus type (3150 Hz, 500 Hz, telephone signal)
- Acoustic environment (AR, RR1, RR2)
- Stimulus presentation (OE, HPM)
- Test–retest factor.

Table 3. Individual and average rms data (°) of normal-hearing subjects for different test conditions.[a]

	500 Hz			3150 Hz			Telephone		
Rms Error (°)	OE	HPM	HPS	OE	HPM	HPS	OE	HPM	HPS
S1	11.6	12.1	15.0	13.1	13.9	20.0	9.0	10.8	11.6
S2	10.4	10.0	9.8	17.1	22.9	27.6	8.1	5.6	6.9
S3	11.1	13.1	9.2	19.4	18.5	26.9	8.2	9.6	7.6
S4	7.6	8.1	10.0	14.3	16.0	17.5	5.5	7.0	9.3
S5	10.4	10.6	12.1	12.2	13.1	24.4	7.2	9.0	10.9
S6	15.1	18.4	18.2	11.1	18.4	25.3	11.0	10.3	17.4
S7	11.6	11.2	10.4	20.3	26.1	26.8	9.5	11.5	10.0
Average	11.1	11.9	12.1	15.3	18.4	24.0	8.3	9.1	10.5
Standard deviation	2.2	3.3	3.3	3.6	4.7	3.9	1.7	2.1	3.5

[a]Tests are done in a reverberant room with a distance between loudspeakers and subject of 1 m (RR1).

Table 4. Individual and average rms data (°) of normal-hearing subjects for different test conditions.[a]

	500 Hz			3150 Hz			Telephone		
Rms Error (°)	OE	HPM	HPS	OE	HPM	HPS	OE	HPM	HPS
S1	14.5	13.6	11.8	19.1	28.5	20.1	9.0	8.5	11.7
S2	13.6	12.6	12.5	18.0	27.1	29.9	9.0	9.6	13.2
S3	13.2	13.6	13.5	17.6	25.9	22.3	9.2	10.6	14.0
S4	13.0	10.6	11.9	17.0	26.0	21.1	7.3	10.2	11.7
S5	11.9	11.6	10.6	17.8	22.4	19.1	8.6	10.8	13.8
S6	21.4	21.7	26.0	23.5	25.6	30.5	10.1	13.1	24.1
S7	18.9	17.1	16.7	17.7	25.9	25.4	16.1	17.6	17.6
Average	15.2	14.4	14.7	18.7	25.9	24.0	9.9	11.5	15.1
Standard deviation	3.5	3.8	5.3	2.2	1.9	4.6	2.9	3.0	4.4

[a]Tests are done in a reverberant room with a distance between loudspeakers and subject of 2.4 m (RR2).

First an interaction between the stimulus type of the main factors and the stimulus presentation is observed ($p = 0.004$). Therefore separate ANOVAs are performed per stimulus. In these three ANOVAs no interactions are observed.

The results are summarized in Table 5. This table illustrates that a significant decrease in localization performance when using measured impulse responses on an artificial head could be detected only when localizing the 3150-Hz stimulus. For this stimulus the OE condition outperforms the HPM condition significantly, by on average 4.7° rms. During this analysis no significant effect of reverberation is observed since the performance of AR is not significantly different from RR1 for all stimuli. However, the significant difference between RR1 and RR2, found for both small-band stimuli, does suggest an impact of loudspeaker distance on localization performance. For the telephone signal no main effect of the acoustic environment was found, and hence no pairwise comparisons are calculated.

2.2 Measurements (CORTEX MK2 Manikin) versus ODEON Software

A second research question motivating these experiments is whether the commercial software package ODEON is able to produce virtual sound signals that can be used to perform reliable localization experiments. This is analyzed by using the ODEON data gathered in the reverberant room. An ANOVA is performed using the main factors.

- Stimulus type (3150 Hz, 500 Hz, telephone signal)
- Acoustic environment (RR1, RR2)
- Stimulus presentation (OE, HPM, HPS)
- Test–retest factor.

Since interactions are found between stimulus type and stimulus presentation, separate ANOVAs are performed for each stimulus. In these ANOVAs interactions are found between stimulus presentation and acoustic environment for the 3150-Hz centered noise band and the telephone signal, motivating separate ANOVAs for each acoustic environment for these stimuli. The results of all analyses are presented in Table 6. A significant difference in localization performance between the HPM and HPS conditions is only found when localizing the high-frequency stimulus in the acoustic environment RR1. In all other experiments both headphone stimuli give the same localization performance. The other pairwise comparisons are somewhat harder to interpret. It is observed that, in general, headphone experiments seem to reduce the localization performance of the 3150-Hz stimulus but not of the 500-Hz stimulus, which was also concluded in one of the previous paragraphs (OE versus HPM and HPS). When localizing a telephone stimulus this trend was observed in the condition RR2.

3 DISCUSSION

The main purpose of the performed tests is related to comparing the listening performance between simulated sound presented via headphones and natural hearing, as well as assessing the quality of simulated BRIRs in comparison with measured BRIRs. Before going into those aspects, we draw attention to the following observation. Regardless of the circumstances, the high-frequency stimulus is localized

Table 5. p values of pairwise comparisons using OE and HPM data for three different acoustic settings.[a]

	500 Hz	3150 Hz	Telephone
AR vs. RR1	1.000	0.354	No
AR vs. RR2	0.074	0.022*	No
RR1 vs. RR2	0.014*	0.047*	No
OE vs. HPM	0.744	<0.001*	0.067

[a] A significant difference between OE and HPM is only observed for the 3150-Hz centered noise band. "No" indicates that no main effect was found, hence no pairwise comparisons were performed.
[*] Value $p < 0.05$.

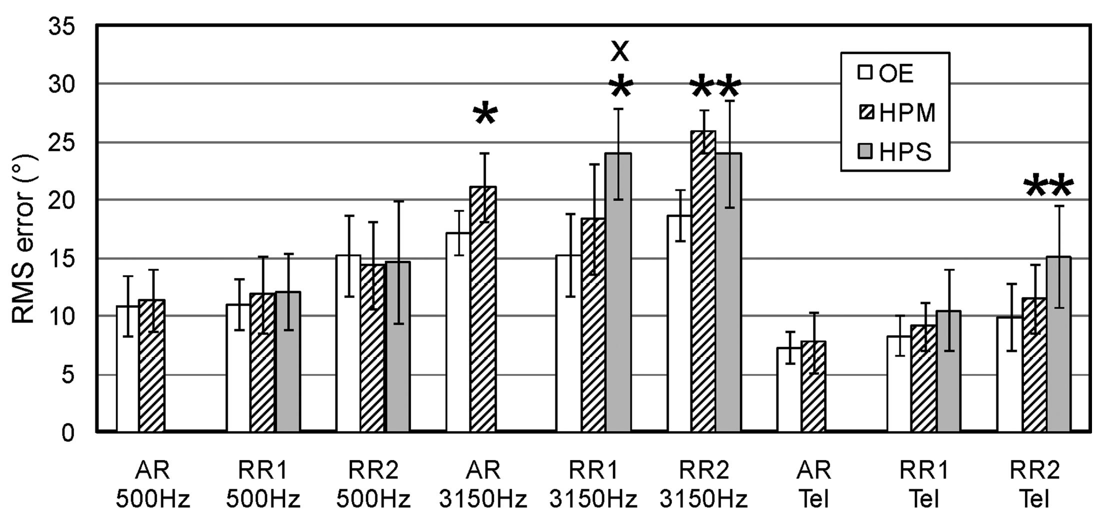

Fig. 5. Summary of mean localization performances of seven normal-hearing subjects together with their intersubject standard deviations. (Full data sets are given in Tables 2–4). *—significant difference with OE condition; ×—significant difference in performance between headphone conditions HPM and HPS. Significant differences are mainly present when localizing high-frequency stimuli. Overall, differences between conditions are fairly small, especially when localizing broad-band or low-frequency stimuli.

least accurately. For the subjects under study the ILD cue, which is predominantly present in the higher part of the frequency spectrum, was apparently processed less adequately than the low-frequency ITD information. In the discussion that follows the possible reasons for deterioration by specific circumstances should therefore be interpreted mainly via their impact on the ITD cue, which is expected to dominate the subjective localization assessment. The presence of visual cues during the listening tests might influence the result as well. For example, because of the visual cues and the presence of loudspeakers in the frontal plane only, the test subjects did not report on the perception of sounds coming from above or behind the head.

3.1 Difference in Localization Performance when Localizing Sound Sources Naturally or when Using Headphones

To address this issue, a comparison of the listening scenarios HPM and HPS is necessary, since they use the same HRTF information. In the condition HPM, impulse responses measured by the artificial head were performed in the acoustic environment of the localization experiment. Afterward these impulse responses were used for the headphone stimulus generation. In the condition HPS, a virtual acoustics software was used to generate the reverberant stimuli used in the headphone experiment. This included the combination of measuring HRTFs of an artificial head in an anechoic environment and modeling the room in the ODEON® software. Table 5 summarizes the statistical analysis done on the data of the anechoic room (AR) and both settings in the reverberant room (RR1 and RR2).

This table indicates that the low-frequency noise is localized equally well using headphones as in real life. This is confirmed by the data in Table 6, which shows that for this stimulus, the performance of both headphone conditions is similar to that of natural localization. This suggests that the ITD cues measured between the microphones of the CORTEX MK2 and which are determined by the positioning of the ear simulators in the manikin, approach the ITD cues normally used by the subjects sufficiently well.

The data for the high-frequency noise component on the other hand show that in general a significant decrease in localization performance is present when localizing sounds under headphones compared to using one's own ears. This is observed in Table 5 and in three out of four pairwise comparisons in Table 6. When analyzing the intrasubject differences in Tables 2–4 decreases in performance on the order of 8° to 9° are often observed, with a maximum decrease of 14.2° (S6, Table 3). Localization of the 3150-Hz centered noise band is mainly based on using ILD information, which is introduced by diffraction and reflections of sounds around and on the head and torso of a human listener. The observed significant decrease in localization performance may be explained by differences in the acoustical properties between an artificial head and a human listener. These differences are due to differences in shape, in material (the artificial head is made from a hard synthetic material) and a lack of clothing and hair, which all have a significant impact on ILD cues.

For a broad-band telephone signal it is observed that when taking all environments (Table 5) into account, no significant decrease in localization performance is found. When isolating the data of the reverberant environment (Table 6), a significant difference is observed, but only if the sound sources are placed at 2.4-m distance from the subject. However, when analyzing the differences made in this condition (Table 4), it is observed that the intrasubject differences between conditions OE and HPM are in the range of −0.5° to 3.0°. The intrasubject differences between OE and HPS are in the range of 1.5° to 5.2° rms, except for subject S6, which showed a decrease of 14.0° rms. These differences may be regarded as acceptable, depending on the experiment.

It can be concluded that significant differences can be present between naturally localizing sound sources or localizing sound sources under headphones. However, these differences are mainly present when localizing narrow-band high-frequency stimuli. When using lower frequencies or broad-band stimuli, no or smaller differences have been observed. The observed differences seem to be due to the artificial head. This conclusion is supported by two studies of Møller et al. In the first study [68] no significant difference in localization performance was found between natural localization and headphone experiments if individual recording were used. In the second study [69] a significant decrease in localization performance was observed when using recordings of eight different artificial heads (not including the CORTEX MK2) in the same localization setup. By isolating the so-called out-of-cone errors, which are related to the horizontal localization performance studied here, seven out of eight artificial heads introduced a decreased localization performance. A second evaluation in the same localization setup, by Minnaar et al. [70], using more recent artificial heads, demonstrated that artificial-head recordings were improving and there is reason for optimism concerning an evolution toward artificial heads approaching real-life performance better and better.

Table 6. p values of pairwise comparisons using OE, HPM, and HPS data in a reverberant room.[a]

		3150 Hz		Telephone	
	500 Hz	RR1	RR2	RR1	RR2
RR1 vs. RR2	0.015*	—	—	—	—
OE vs. HPM	No	0.126	0.001*	No	0.044*
OE vs. HPS	No	0.003*	0.030*	No	0.042*
HPM vs. HPS	No	0.021*	0.966	No	0.094

[a] A significant difference between HPM and HPS is only observed when localizing the 3150-Hz centered noise band arriving from a 1-m distance from the subject. "No" indicates that no main effect was found, hence no pairwise comparisons were performed.
* Value $p < 0.05$.

3.2 Difference in Localization Performance when Generating Stimuli with Measured Impulse Responses or with Virtual Acoustics Software

Evaluations were performed using HPM and HPS stimuli in a reverberant room. Table 6 indicates that a significant difference between HPM and HPS is observed only when localizing high-frequency sound sources that are positioned at 1 m from the subject. The errors introduced by the ODEON® software for this specific condition range from 0.7 to 11.3°. In contrast with condition RR1, ODEON® does not introduce large decreases in localization performance in condition RR2. Moreover, in this condition performance even improves for five out of seven subjects. This seems contradictory. However, when examining the HPM data, which is the reference condition for this research question, of the 3150-Hz noise band, it is observed that the RR1 condition outperforms the RR2 condition significantly. By using the ODEON® software the performance of RR1 is decreased to the level of RR2. In other words, ODEON® somewhat affects the localization performance of a high-frequency stimulus if a high performance is obtained at the baseline condition. When using low and broad-band stimuli no significant differences are observed (Table 6).

It can be concluded that ODEON® software introduces some binaural cue distortion compared to HPM stimuli when using high-frequency signals. Possibly this is related to the extrapolation of the horizontal-plane HRTF used for all sagittal angles. These distortions lead, to a certain extent, to a significant decrease in localization performance. If the originally obtained localization performance by using HPM stimuli is moderate, ODEON® will not introduce additional distortions.

3.3 Influence of Reverberation on the Natural Localization of Sound Sources or on the Localization of Sound Sources under Headphones

During these experiments two different extreme acoustic environments have been studied—the anechoic room and the reverberant room. By observing the data in Table 5 it is clear that for all stimuli, reverberation time as such does not influence localization performance (AR versus RR1) when loudspeakers are sufficiently close to the subject. However, interestingly a significant difference is observed when changing the distance between loudspeakers and subject (RR1 versus RR2). The fact that the reverberation does not affect localization performance can be explained by the so-called precedence effect, which is also known as the law of the first wavefront. (For an overview on the precedence effect see [71].) The precedence effect is based on the ability of the human auditory system to associate the direction of arrival of a sound source with the direction of arrival of the direct sound. The time interval in which this takes place is called fusion zone. Outside the fusion zone, reflecting sounds are perceived as being echoes, which have their own direction of arrival. These evaluations show that the precedence effect avoids significant differences in localization performance between two very extreme acoustic environments.

The significant difference in performance between conditions RR1 and RR2 is less straightforward to explain. Two interpretations are possible. The first is that localizing sound sources positioned at 2.4-m distance is less accurate than localizing sound sources at 1-m distance in general. However, this cannot be concluded from the data, since no evaluations were done in a 2.4-m setup in the anechoic environment. Moreover, in the work of [72] the claim was made that ITD and ILD cues are virtually independent of distance if the sound sources are positioned beyond 1 m. The difference in localization performance between scenarios RR1 and RR2 can be explained in an alternative way by inferring that due to the lower direct-to-reverberant ratio, the first wavefront in RR2 is too weak with respect to the subsequent sound from reflections to allow for a correct sound localization of the sound source [57]. This suggests that placing the sound sources further would affect the localization performance even more. However, this was not investigated, because of the limited room dimensions. We also limited the stimuli in this study to sounds with a fairly transient character. One can expect that localization on the basis of continuous stimuli would suffer more in a reverberant situation.

4 CONCLUSION

A comparison was made between localizing sounds in a natural way and localizing sounds sources in stimulated binaural sound presented via headphones. Two different headphone conditions were evaluated. First impulse responses were measured between loudspeakers and an artificial head. Subsequently they were used to generate the headphone stimuli. A second set was generated by using ODEON® software, enabling the acoustic modeling of virtual environments.

Presenting listening stimuli via headphones tends to decrease the localization performance only slightly when localizing narrow-band high-frequency stimuli. The use of an artificial head for generating the HPM and HPS stimuli may explain these differences, since the acoustical properties of an artificial head are different from those of a human listener, thereby generating less natural ILD cues. Also, for headphone tests neglecting the sagittal angular dependence of the measured HRTF could have a slightly deteriorating effect. When localizing narrow-band low-frequency signals or a broad-band telephone signal, either no or a small decrease in performance was observed since geometrical head details are less relevant for long wavelengths.

In most of the virtual scenarios the localization performance is almost as good as the one observed for the natural scenario. Headphone experiments show little decrease in localization performance compared to measured impulse responses in only one out of six test conditions, namely, when using narrow-band high-frequency signals.

Reverberation has no significant influence on localization accuracy if the distance between receiver and loudspeaker is only 1 m. This may be understood in view of the preserved dominance of the direct sound helping the listener to localize the source. However, in the same room, for a larger distance (2.4 m) between loudspeakers and subject, the localization performance deteriorates. This indicates that the impact on the localization performance of a decreasing direct-to-reverberant sound ratio [57] is higher than the impact of reverberation as such. The result also shows that sound source localization is more robust under reverberant conditions than speech recognition, which typically deteriorates rapidly in the presence of reverberation, because of the highly energetic noise background resulting from long persisting echoes. Even a moderate deterioration of sound source localization performance can thus be seen as an indicator for a drastic reduction in speech intelligibility, partly due to the background noise, and partly due to the loss of effective signal-to-noise enhancement that is brought by binaural sound reception.

The good overall agreement between the simulation- and measurement-based results in localization tests proves that the simulation approach does a good job in terms of predicting BRIRs, useful for directional localization perception tests in the frontal horizontal plane. In support of this conclusion it is worth mentioning that in a related paper [73] it was shown that using predicted BRIRs for sound source localization tests in a typical virtual classroom, angular asymmetry was revealed in the localization performance, which was due to the asymmetric location of sources and listening subject with respect to the objects in the classroom.

Future research should determine whether localization performance differences at high frequencies persist when the HRTF of the artificial head is replaced by an HRTF that is recorded individually by placing intraear microphones in individual listening subjects, or by the HRTF obtained from finite-element models of artificial and test subjects' heads.

This research is also a first step toward verifying whether using simulated BRIRs in listening tests in virtual acoustic scenarios is adequate for speech recognition assessment, both for normal-hearing persons and for hearing-impaired persons wearing hearing aids with cue processing algorithms to be tuned for real-life circumstances.

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Prediction of statistical noise values in an urban square by using auralisation

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ABSTRACT

The main goal of the study presented in this paper is to investigate whether it is possible to synthesize a virtual urban soundscape based on information about the functionality of the place and the activity occurring in it, in order to then predict statistical noise values of sound in situ (Experiment No.1). The second goal is to analyze the response of people to different traffic noise levels present in a virtual square by means of laboratory listening tests (Experiment No.2). In view of setting up the experiments, first, binaural acoustic recordings were made in situ. A typical local acoustical situation in this public place was then simulated in Odeon® software. Auralization of the urban square was carried out for different calculation algorithms and parameters. The real and virtual urban environments were also compared with an anechoic situation (assuming 100% absorption of all model surfaces). Subjective impressions about the typical acoustical situations in the square were obtained from listening tests, performed in laboratory conditions. The stimuli used in the tests were based on synthesized virtual urban sound, combining binaural in situ recordings with binaural auralized sound. We show to which extent acoustical modelling can serve to predict noise levels in an urban public square, and thus address the question if acoustic modelling can be used by decision-makers when developing new or renovating existing urban public places. This study also sheds a light on the levels of traffic noise that are found pleasant, disturbing and unbearable for the site of interest.

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1. INTRODUCTION

Virtual synthesis of sound is not a new topic of interest an has often been used in room acoustics, virtual reality simulations, in hearing research and even in computer games.[1] Application of the virtual synthesis of sound for urban soundscape research can be also found in a few works.[2] However, in most of the works about soundscapes, most of the attention is given to the subjective evaluation of acoustic environments by questionnaire surveys, semantic categories or by developing numerical descriptors.[3-5] Urban planners and decision makers often ask about the quality of acoustic prediction in terms of possibility to deliver reliable information about the soundscape of a place which is in the stage of designing. The study presented here deals with the prediction of statistical values of noise and investigates the human perception of these levels.

2. METHODS

A. Measurement methods

The in situ measurements done for this study resulted in binaural recordings by using in-ear microphones and an M-Audio® solid state recorder. The recording system was calibrated in the laboratory in order to calculate correct absolute sound pressure levels from all recorded samples. The sound analysis was done in partially in 01dB® software and in Matlab®.

B. Simulation method

For the room acoustical simulations in this study, ODEON® software was chosen. This software uses a hybrid algorithm in which the simulation of the Impulse Response (IR) of rooms is performed in two parts. The early part of he IR is based on early reflections, which are calculated by combining an Image Source Method (ISM) and Early Scattered Rays (ESR). The late part of the IR, i.e. the part containing late reflections, is calculated by using a Ray Tracing Method (RTM) that includes an advanced scattering algorithm. The length of the first part of the IR can be chosen by the software user via the so-called Transition Order (TO). This is the maximum number of image sources per initial ray. The Binaural Room Impulse Response (BRIR) in Odeon is calculated at the receiver point by filtering the calculated room impulse response with the Head-Related Transfer Function (HRTF) for respectively the left and right ear. The thus generated BRIR was then later convolved with anechoic recordings, in order to obtain auralized sound for the site of interest.

C. Methods for noise analysis

In order to be able to describe all important features of sound level fluctuations, methods for statistical analysis of noise have been developed, in which statistical values L_x are determined. L_x expresses as the value of sound pressure level that was exceeded during x % of the measuring time. In this study the statistical parameters L_5 and L_{95} were calculated and analyzed.

Another parameter used in this study is the equivalent noise level $L_{A,eq}$, which is one of the most frequently used descriptors of environmental noise. Most of the sound level meters have a direct option for obtaining this value automatically. $L_{A,eq,T}$ gives the level of continuous steady sound within a time interval T, which has the same effective (rms) sound pressure as the measured sound of which the pressure varies with time. The definition of $L_{A,eq,T}$ is given by:

$$L_{A,eq,T} = 10.\log\left(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2}\frac{p_A^2(t)}{p_0^2}dt\right) \tag{1}$$

where p_A is the instantaneous A-weighted rms sound pressure at time t, p_0=20 µPa is the reference sound pressure level, $T = t_2 - t_1$ is the measuring period.

2. EXPERIMENTS

A. Description of the case study

The Grote Markt site is the main square of the city of Leuven. The square is surrounded by buildings such as the town hall, St. Pieter's church, several restaurants and apartment buildings. Due to many different kinds of sound sources and diverse social activities present in this square on different days and seasons in the year, the soundscapes occurring on this site are quite interesting. The overall most typical sounds occurring on the site are definitely human voices, human steps, bicycles, church bells and busses passing by 10 times per hour during working days. During the past years several changes were made in this square, mainly related to a reduction of its accessibility by cars for reasons of functionality, noise and safety. Nowadays, the square is considered as a pedestrian zone where only city buses are allowed to enter.

Figure 1 : Grote Markt in Leuven, Belgium, view on the part of the square with restaurants

B. Binaural recordings in situ

A first set of calibrated binaural recordings were performed in situ by using in-ear microphones and a solid state recorder on a warm summer evening and close to the restaurants, in a time period when no busses were passing.
The second set of recordings was done during winter, when no human voices were present on the square and the sound of the passing bus was dominant. Also the stationary traffic noise was recorded for future listening tests.

C. Simulations

Our 3D computer model of Grote Markt was based on measured dimensions of the square in situ by using a laser distance meter. A simplified virtual model was constructed in Odeon9.2® (Figure 2). Grote Markt has an irregular shape but roughly its dimensions can be estimated to 120 x 32 m. For the sake of acoustical simulations, parts of the streets that terminate on this square were included in the model, resulting in a total calculation domain of about 240 x 140 m

surface (Figure 2). Sound absorption and scattering coefficients of the surrounding buildings and ground surfaces were estimated based on a visual check in situ.
The model of the square was closed in a box with boundaries defined as surfaces with a sound absorption coefficient α = 100%, expressing an open air situation. The BRIRs of the 3D model were obtained from a simulation of a multisource environment with 102 sound sources. Each of the 102 BRIRs were convolved with appropriate anechoic samples like human speech, walking people, various restaurant sounds, such as sounds or the cutlery or glass etc.

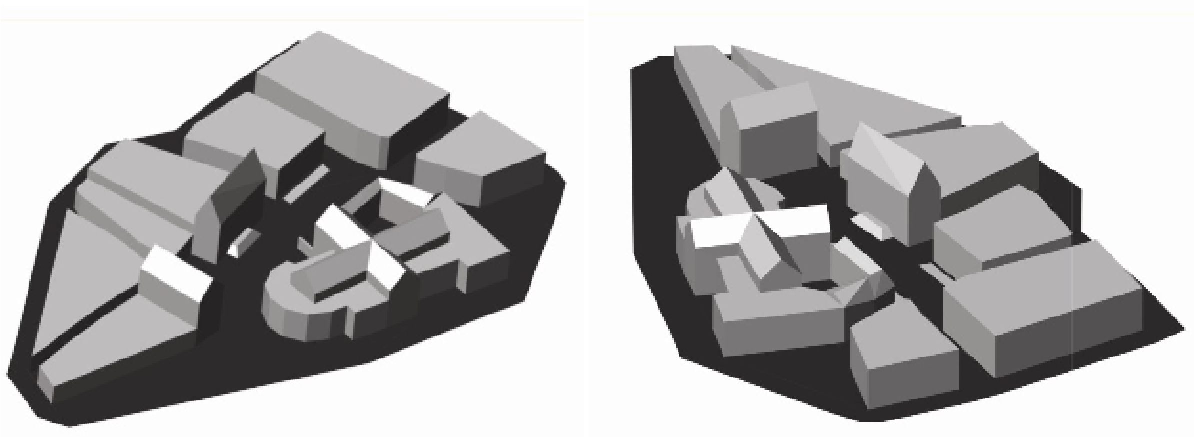

Figure 2 : 3D model of Grote Markt including surrounding buildings

These sound sources were regularly distributed into two virtual outdoor restaurant areas (Figure 3): 58 speaking people were simulated in zone A and 44 in zone B. The auralized samples were mixed to final audio samples (wave files) expressing a summer evening soundscape typical for Grote Markt. The final simulated sound samples were 5 minutes long, and were analysed in the same way as the recorded one, i.e. by using the statistical noise analysis (see description of the Experiment No.1).
For the listening tests in Experiment No.2, shorter sound samples of about 15 seconds duration, containing the typical features of the simulated soundscape, were prepared (see description of the Experiment No.2).

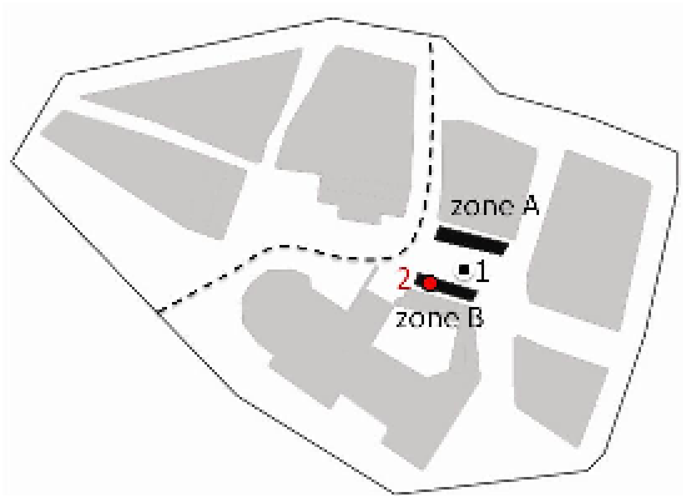

Figure 3: Ground plan of Grote Markt with an indication of the outdoor restaurant zones A and B, and of the two listening positions: 1. in the middle of the square; 2. at the table in the restaurant. The dashed line indicates the trajectory of the buses.

D. Description of the two experiments performed in this study.

In Experiment No.1, a comparison is made between the measured and predicted statistical noise levels L_5, L_{95} and L_{Aeq}, which are determined for sound samples containing a typical soundscape on the square during evening hours in the summer holiday. The length of the analysed samples was 5 minutes in measurement and also in all simulations. Simulations for different TO numbers (0 to 2) and for a free field situation were compared with each other and with measurement.
Although the prediction of the soundscape in an urban public place is rather difficult, questions from urban planners and decision makers are often related to prediction of the acoustical ituation outdoors and to the proposals of noise reduction or pleasant soundscape creation.
This short experiment thus serve as a first try in the row of our the research studies on this topic.

Experiment No. 2 is based on listening tests that use virtual sound and investigates the subjective perception of the traffic noise level for two listening scenarios, based on the activity of the person. First, a virtual listener was located in the middle of the square walking between two virtual outdoor restaurants. His or her activity was defined as being waiting for friends. In the second simulation, the listener was supposed to sit on the terrace of one of the restaurants, close to the talking people. In both scenarios, the sound level of the restaurant sound, i.e. talking people, were constant (at the level of 54 dB (A)). On the other hand, the noise from the traffic was mixed on different sound levels, in order to investigate its disturbing character.
The stimuli played to listening subjects via headphones were created by mixing auralized restaurant sound from the Odeon® simulation with 22 noise recordings of a different level. Half of them were based on stationary traffic noise recording and the other half contained also the sound of a bus passing by. Stimuli were played randomly, each twice. The task of the listening subjects was to imagine him or her self in the sketched situation, and to indicate whether the traffic noise in the given acoustic scenario was (1) too silent, (2) pleasant, (3) acceptable, (4) noisy or (5) disturbing.
Listening tests were performed in the silent anechoic room by using a listening unit of Head Acoustics® with open headphones. The system was calibrated before each listening session.
10 normal hearing listening subjects of the age between 21-34 participated in the experiments.

3. RESULTS AND ANALYSIS

A. Experiment No.1

Results of the L_{Aeq} are shown in Table 1. The simulated $L_{A,eq}$ was around 57 dB in all simulations (TO0, TO1 and TO2) , i.e. only 3 dB less than the value observed in the measurement. The predicted value for the free field situation was 53 dB, which is 7 dB lower than the value observed in situ. This shows that the influence of buildings in this situation was ca 4 dB.
Simulated alternatives, in which only 50 people (instead of 100) were talking, gives a logical drop in values in ca 3 dB.

Table 1 Values of $L_{A,eq}$ for different numbers of speaking people: comparison between simulations and measurements in situ

	Simulation with TO0		Simulation with TO1		Simulation with TO2		Simulation of free field situation		Measurement
Number of talking people	102	51	102	51	102	51	102	51	100 -150
$L_{A,eq}$ [dB]	56,8	53,8	56,4	53,6	56,3	51,7	53	51,4	60,3

L_5 was only 58 dB for all simulations whereas it was 63 dB in situ. The simulated L_{95} value was 55 dB, compared to 52 dB measured. This means that the dynamics of the measured value was larger than the simulated as difference L_5 - L_{95} was ca 4 dB in simulations and ca 9 dB in measurement. These differences are likely to be caused by the different crowd behaviour between the simulated and measured situation. The results show that in a real situation, the speech of the crowd contains slow fluctuations, e.g. 2 -5 per minute, independent from the intrinsic fluctuations in speech. These slow fluctuations were not sufficiently simulated when random breaks in speech of every person were included in the auralized sound. Fluctuations in the speaking crowd are probably not completely random. People have a tendency to adapt their speaking level to acoustical an visual circumstances. A relatively high value of subjectivity plays a role as well. The peaks and the relatively silent periods of the crowd-sound were thus not enough pronounced in the automatically auralized sound.
The frequency spectrum of the recorded signal was observed to be more flat than in the simulated one, which contained more dominantly speech sound. In a real situation there is more background noise with a rather flat spectrum, which gives a rather frequency independent contribution in the frequency spectrum of real soundscapes.

B. Experiment No. 2

The result of the Experiment 2, depicted in Figure 4, shows the people's perception of traffic noise under two Listening Scenarios (LS), i.e. when standing in the square (LS1), or, when sitting on the terrace of the restaurant in the square (LS2). A similar subjective evaluation was observed for these two listening scenarios and no significant difference between the two activities (listening scenarios) was observed.

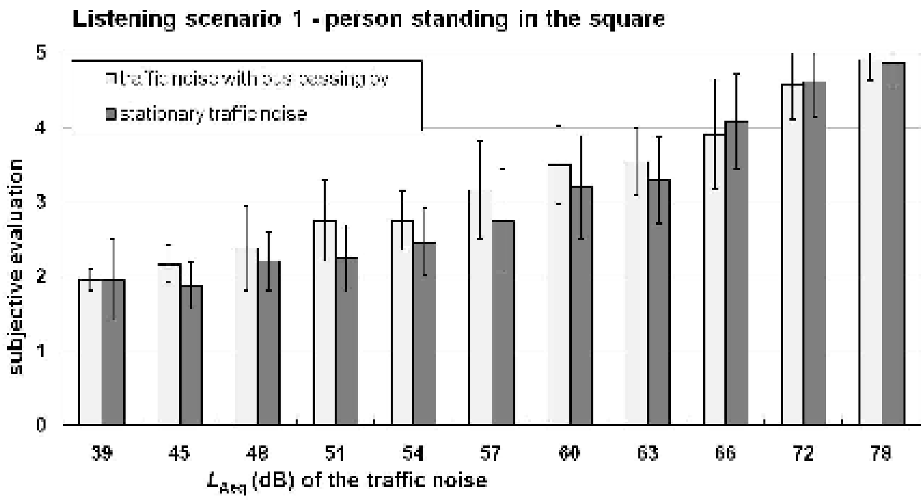

Figure 4: Results given as average values + standard deviation from the listening scenario 1. Subjective evaluation was understood as: 1 - too silent, 2 - pleasant, 3 - acceptable, 4 - noisy or 5 - disturbing.

Figure 4 shows that on average people did not perceive any of the stimuli as "too silent". This is due to the fact that the most silent sample was based on a crowd of people speaking on a level 54 dB (at the listening position) which is not really silent sound. Traffic noise was in both cases perceived as pleasant when its level had reached the same values as the human speech, i.e. values between 50 - 55 dB. Values of noise between 60 – 66 dB were considered as acceptable and the annoying level of noise started around 66 – 68 dB. Values reaching about 80 dB were for all the listening subjects assigned as "unbearable".
Slight differences were found between the stimuli with the bus passing by and the stimuli with stationary traffic noise, where the samples with a bus passing by were found more "annoying".

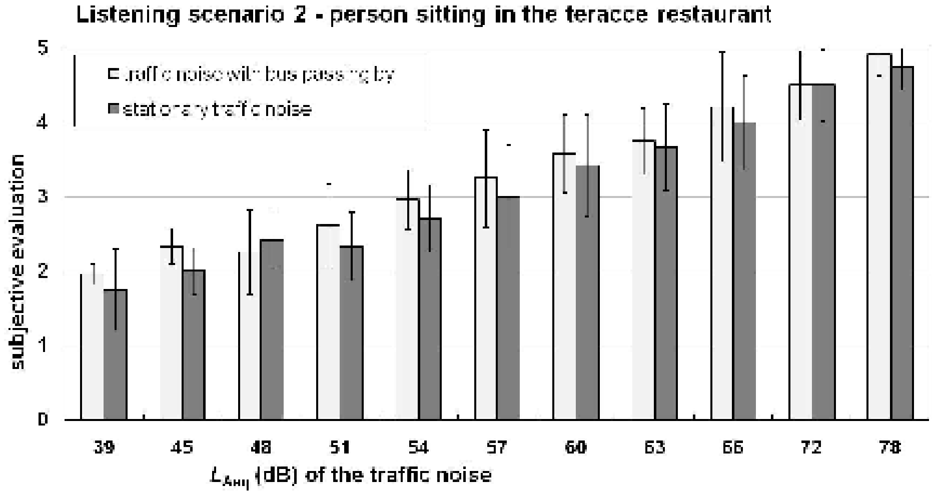

Figure 5: Results given as average values + standard deviation from the listening scenario 2. The subjective evaluation was defined as: 1 - too silent, 2 - pleasant, 3 - acceptable, 4 - noisy or 5 - disturbing.

3. CONCLUSIONS

This study has shown to what extent statistical values of noise can be used in urban soundscape prediction for given activity in a city square. It seems that the prediction of equivalent noise levels is satisfactory when simulating cases similar to our case study. The prediction of peak values defined through L_5 as well as L_{95} values was less accurate. This study has highlighted the difficulties of adequate human crowd-sound auralisation and suggests further investigation.

The perception of traffic noise by a person when being surrounded by people in the square, can be summarized as follows: situations in which the level of the traffic noise was not stronger than the one of human voices, i.e. 50 - 55 dB, was considered by most of the people as pleasant. According to the performed listening test noise values till 66 - 68 dB are found acceptable.

ACKNOWLEDGMENTS

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URBANISME

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Densité vécue, densité perçue

Cet article est extrait du rapport thématique sur la densité établi dans le cadre de la recherche "Design and renovation of urban public spaces for sustainable cities (DRUPSSuC)", financée par la Politique scientifique fédérale qui vise l'amélioration de la qualité du cadre de vie au travers des espaces publics.

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Architecte (CREAT-UCL)

Définition de la densité

Le dictionnaire commun définit la densité comme "*qualité de ce qui est dense (compacité, épaisseur)*"[1]. Cette notion évolue suivant la discipline. Ainsi, en physique, le terme densité désigne le "*rapport entre une masse volumique d'un corps et celle d'un autre corps servant de référence*"[2].

Dans le domaine de l'urbanisme, il se décrit en termes de critères objectifs, quantitatifs - densité "réelle" - et de critères plus subjectifs, qualitatifs - densité "perçue".

La densité réelle

La densité réelle se définit par une formule mathématique établie sous forme de rapport entre une quantité ou un indicateur statistique (nombre d'habitants, d'emplois, de logements, ...) et une valeur de référence qui peut être une surface (densité surfacique), un volume (densité volumique) ou une longueur (densité linéaire).

Il existe différents calculs de densités réelles qui peuvent être analysés en regard de l'indicateur de référence, de la surface étudiée et de l'échelle abordée. C'est pourquoi, parler de forte ou de faible densité sans préciser s'il s'agit de densité bâtie, de logement ou encore sur quelle surface on se base est ambigu.

Vincent Fouchier précise dans *Les densités urbaines et le développement durable, le cas de l'Ile-de-France et des villes nouvelles* que le terme densité devrait systématiquement s'accompagner d'un qualificatif qui préciserait tant l'indicateur que la surface de références. Dans cette optique, il distingue la densité de "contenant", c'est-à-dire l'enveloppe, le bâti, ... et la densité de "contenu" - l'habitant, l'usager. Il apporte une première précision en regard de l'indicateur de référence.

La seconde notion à préciser est la surface étudiée qui peut être nette ou brute. Une surface nette ne tient compte que de la surface pour une occupation donnée, par exemple le logement, les surfaces de loisirs, de travail, ..., et leurs annexes (influences de la structure, de la surface réservée au parking, etc.). La densité par surface brute tient compte de la totalité de l'espace, en ce compris les surfaces connexes à l'occupation principale (voiries, abords, ...).

Enfin, la troisième notion, l'échelle ou le périmètre abordé définit l'approche de la densité. On peut ainsi se référer à une échelle micro, l'échelle d'un bâtiment, de l'îlot (par ex., le nombre de logements par habitation), ou une échelle plus macro, le quartier, la commune, le secteur statistique (par ex.: le nombre de logements par hectare).

Afin d'illustrer les variations de la densité réelle suivant l'indicateur et l'échelle abordés, voici différents types de calculs possibles. Ils ne constituent pas une liste exhaustive mais plutôt une base de référence en termes d'évaluation de la densité réelle.

Indicateur / Echelle	Densité de contenant		Densité de contenu		
	Bâtiment	Logements	Habitants	Habitants + Emplois	Emplois
Surface bâtie	P/S ou plancher/sol,				
Parcelle	CES ou coefficient d'emprise au sol COS ou coefficient d'occupation du sol	DR ou densité résidentielle			DE ou densité d'emploi
Ilot	COS			DAH ou densité d'activité humaine	
Quartier					
Ville			DP ou densité de population	DAH ou densité d'activité humaine	
Commune					

P/S ou le rapport plancher-sol donne une première indication de la densité perçue car il tient compte du nombre de niveaux.

CES ou le coefficient d'emprise au sol est le rapport entre l'emprise au sol totale des bâtiments et la surface de l'îlot sur lequel ils sont implantés. Contrairement au COS, il exprime une réalité.

COS ou le coefficient d'occupation du sol est le rapport entre les m² de surface hors œuvre nette (SHON) [3] et détermine la densité de construction admise sur une parcelle; il s'agit du "droit à bâtir" sur un espace donné. Il exprime une possibilité. La mesure du COS est imposée en France dans le cadre des Plans locaux d'urbanisme (PLU).

COS à l'échelle de l'îlot exprime la formation traditionnelle du tissu urbain, la différence entre le tissu lâche du périurbain et la compacité du centre ville.

DR ou la densité résidentielle définit une densité moyenne de logements à l'hectare et permet d'établir des seuils pour les besoins en équipements ou pour comparer des territoires différents.

DP ou la densité de population est obtenue en divisant le nombre d'habitants par la surface généralement en km² ou en hectare. Cette mesure permet de comparer des villes de tailles différentes. Elle détermine la concentration de population sur un secteur donné.

DAH ou la densité d'activité humaine est une mesure utilisée notamment par Vincent Fouchier dans son étude *Les densités urbaines et le développement durable, le cas de l'Ile-de-France et des villes nouvelles;* elle rend compte de l'intensité d'usage de la surface.

DE ou la densité d'emplois est une des mesures pour analyser la mixité fonctionnelle d'une surface donnée. Elle s'obtient en divisant le nombre d'emplois par la surface étudiée.

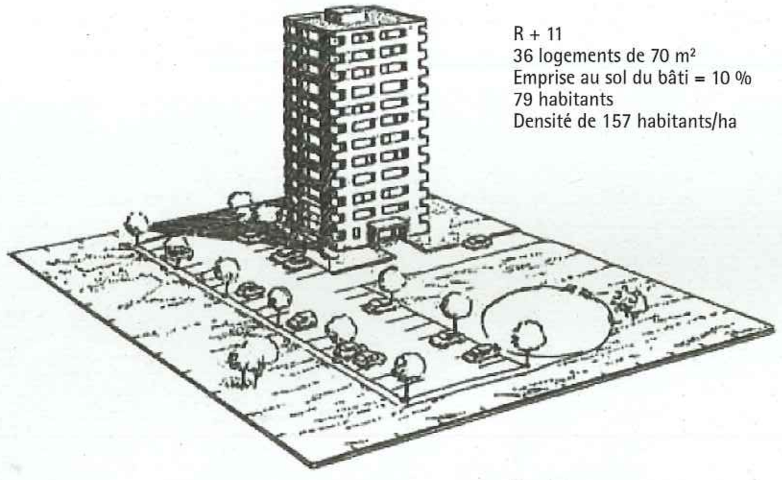
1 J. Rey-Debove et A. Rey (sous la dir. de) (1993), *Le Petit Robert dictionnaire de la langue française*, le Robert, Paris, p. 590.

2 J. Rey-Debove et A. Rey (sous la dir. de) (1993), id.

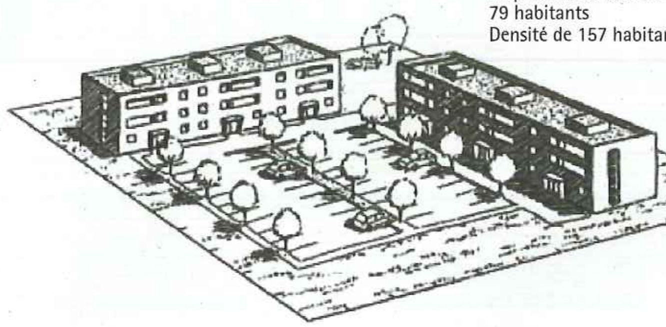
3 SHON ou surface hors œuvre nette ne prend en compte que les surfaces habitables (tout sauf les caves et les garages) sans l'épaisseur des murs; au contraire, le SHOB ou surface hors œuvre brute prend en compte toutes les surfaces et l'épaisseur des murs.

Si on prend le calcul du COS (coefficient d'occupation du sol), on constate qu'il n'existe pas de lien direct entre le résultat et la forme urbaine. A densité égale, les formes urbaines et, par conséquent, la perception de l'espace varient. La densité réelle n'est pas une condition nécessaire ni suffisante pour créer un sentiment d'oppression ou au contraire de confort. Beaucoup d'autres facteurs interviennent qui changent la perception de l'espace.

Chaque exemple a une surface de terrain de 5.040 m² et une SHOB totale de 2.520 m², soit un COS brut de 0,5



R + 11
36 logements de 70 m²
Emprise au sol du bâti = 10 %
79 habitants
Densité de 157 habitants/ha



R + 2
36 logements de 70 m²
Emprise au sol du bâti = 17 %
79 habitants
Densité de 157 habitants/ha

R + combles
24 logements de 105 m²
Emprise au sol du bâti = 33 %
67 habitants
Densité de 133 habitants/ha

N.B.: Le nombre d'habitants est calculé selon le nombre moyen de personnes par ménage en France en 1990 (2,8 personnes pour l'individuel et 2,2 pour le collectif).

Source: V. Fouchier (1997), Les densités urbaines et le développement durable, le cas de l'Ile-de-France et des villes nouvelles, éd. du SGVN, Paris.

La densité perçue

L'image collective dévalue la densité. Les fortes densités sont le plus souvent associées à de l'insécurité, à des problèmes de pollutions, au bruit, ... Il suffit de regarder l'image des "tours ou des barres", véhiculée au travers des médias notamment en France, ou encore dans le monde du cinéma comme, par exemple, dans le film allemand *Métropolis* (1927) où la ville basse est écrasée sous le poids du travail pour faire fonctionner la mégalopole, ou encore dans le film, plus récent, *Le cinquième élément* de Luc Besson où la base de la ville est prise dans un brouillard de pollution constant.

Selon une étude française menée par l'Observatoire de la ville en janvier 2007[4] "*spontanément et en premier, la densité génère des représentations négatives qui se déclinent en nuisances (35 % des citations): nuisances sur la qualité de vie (22 % des citations) avec un espace de vie restreint, l'insécurité, la peur, la solitude et l'anonymat auxquels renvoie la foule; nuisance sur la santé (5 % des citations), en termes de fatigue, stress; nuisance sur l'environnement (2 % des citations), la densité générant trafic et pollution. L'appréhension objective de la notion n'est pourtant pas absente, la densité humaine et les tentatives de définition objective de la densité représentant chacune 22 % et 21 % des réponses. Vient ensuite une évocation des formes d'habitat (14 %) et de l'organisation de l'espace (4 %). D'une façon générale, les nuisances de la densité sont fortement représentées parmi les classes aisées (45 % de citations), les cadres et professions intellectuelles (40 %) et les diplômés de l'enseignement supérieur (44 %). Au final, près de deux tiers des Français (65 %) pensent que la densité est quelque chose de négatif, dont 17 % déclarent qu'elle est quelque chose de très négatif. Cette perception est homogène, bien qu'également surreprésentée parmi les classes aisées (74 % des répondants)*".

Pourtant, est-ce vraiment la densité en soi qui pose question ou plutôt la forme urbaine, les grands espaces monofonctionnels, ...? La densité réelle est un premier indicateur mais non suffisant pour rendre compte de "l'impression de densité". Il est donc primordial de distinguer densité réelle et densité perçue.

[4] Collectif - Observatoire de la ville (2007), *Les français et leur habitat - Perception de la densité et des formes d'habitat*, principaux enseignements du sondage réalisé pour l'Observatoire de la ville du 10 au 12.1.2007, p. 10.

La densité perçue se réfère à des approches plus culturelles et psychologiques de l'espace qui ne correspondent pas forcément à des variables physiques. Elle se base sur des impressions propres à chacun en lien avec la hauteur des bâtiments, la continuité du front bâti, l'ambiance spatiale, etc. Elle varie selon les individus, suivant ses références personnelles et culturelles et est, par conséquent, plus difficile à appréhender.

Les facteurs principaux qui semblent influencer notre perception de l'espace sont la culture et le psychologique.

Densité perçue: facteurs culturels

La culture se caractérise par un ensemble de connaissances communes à un groupe qui fixe une identité. Chaque culture établit ses normes, c'est-à-dire ses attentes sur la façon de se comporter dans diverses situations. La culture, de par ses normes, conditionne nos attentes et donc la perception que l'on peut se faire d'un espace ou de la densité. Le mot densification, dans la culture occidentale, effraie. Ainsi, Vincent Fouchier, dans son article *La densification: une comparaison internationale entre politiques contrastées*[5], constate que, dans certains travaux de recherche ou de programme d'urbanisme, le terme est remplacé par des mots à connotation moins négative. En Grande-Bretagne, on parle de régénération, d'intensification urbaine, en Allemagne, de développement intérieur et en France, de "deuxième couche"[6]. Pourtant, cette image négative de la densité est récente. Au Moyen Âge, la ville étant limitée par ses remparts, les constructions présentaient alors une densité bâtie importante. Les habitations sont hautes et étroites, les parcelles peu profondes. Au XIXe siècle, la ville se complexifie et change d'échelle. C'est l'époque des hygiénistes, notamment de Haussmann qui prévoit de rendre la ville plus aérée et lisible. Pourtant, loin de dédensifier la ville, Haussmann augmente le niveau des immeubles et construit sur presque toute la superficie de la parcelle. Dans les années 60-70, la période d'après-guerre favorise la construction des grands ensembles de den-

[5] V. Fouchier (1995), *Une comparaison internationale entre politique contrastée, Densité et espacement, Les Annales de la Recherche Urbaine*, n° 67.

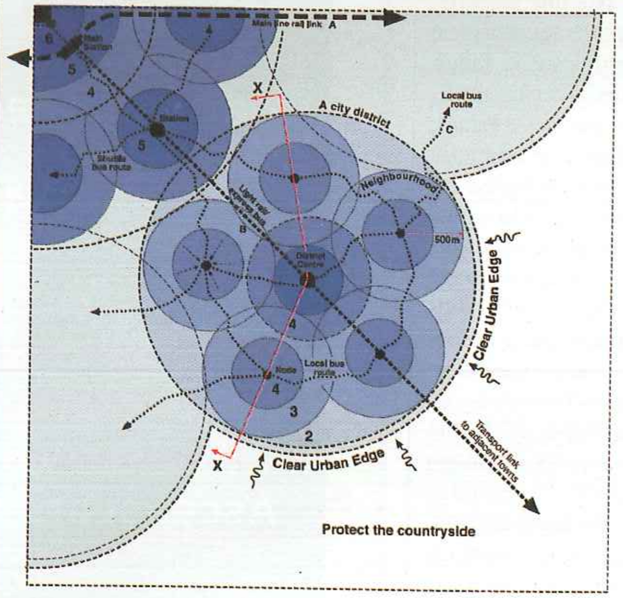
[6] Le terme est employé dans des travaux pré-opérationnels à Evry.

site bâtie plus faible que les immeubles haussmanniens du XIXe siècle. L'heure actuelle est à la construction de lotissements pavillonnaires type maison quatre façades. Comme on le constate au travers de ces exemples, la perception de la densité bâtie a évolué au cours de l'histoire reflétant la culture de son époque. Cette idée tend à être corroborée par l'analyse des repères historiques en matière de densité réalisée par l'Institut d'Aménagement et d'Urbanisme en région Ile-de-France[7].

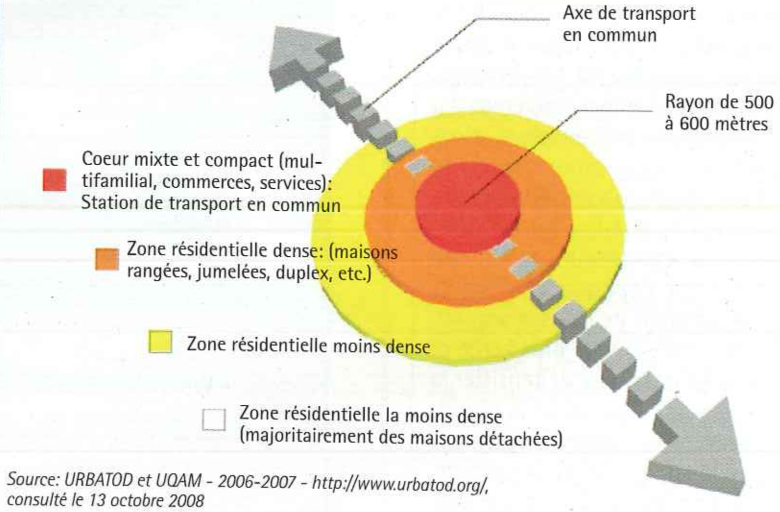
Ainsi, dans notre culture occidentale actuelle, les fortes densités bâties semblent être bien vécues lorsqu'elles se situent dans un "centre". Selon la théorie des lieux centraux de W. Christaller et A. Lösch, le "centre" est le siège de la distribution des biens et des services au contraire des "périphéries", lieux de résidence des consommateurs. Son influence dépend de sa portée géographique et de la diversification et de l'importance de l'offre. Prenons l'exemple des centres d'affaires dans les grandes villes occidentales. Généralement, ils regroupent la plus grande concentration de services mais également des centres commerciaux, des offres de biens diversifiées et en quantité importante. Surtout, les centres d'affaires se caractérisent par des gabarits importants, voire même les plus importants de la ville. La forte densité bâtie semble y être sinon appréciée, tout du moins acceptée.

Un autre facteur intervenant dans la perception positive des fortes densités bâties est la diversité des fonctions et des populations rencontrées. Dans l'étude menée par l'Atelier parisien d'Urbanisme (Apur), la question a été posée de savoir quel tissu urbain est le mieux apprécié. Pour ce faire, une analyse comparative de quatre quartiers parisiens a été menée en 2003. L'analyse se base tant sur des critères objectifs (le calcul du COS, de la densité de fréquentation, à savoir population et emploi, densité brute, nette), du profil sociologique des secteurs et d'une enquête sur la perception de la densité. Cette dernière a été évaluée à l'aide d'un questionnaire qui s'articule sur des thèmes liés à la satisfaction du cadre de vie (perception du cadre architectural et urbain, vie sociale, services et équipements, nuisances, maintenance, ...). Cette étude semble apporter déjà certaines conclusions[8]: *"Les fortes densités semblent bien vécues, lorsqu'elles s'accompagnent d'une diversité des populations et des activités susceptibles de créer une véritable animation"*[9].

Ces principes sont également appliqués en matière de développement durable. Dans le modèle de l'urbanisme durable[10], la notion de "centre" peut se définir comme un pôle concentrant une mixité de fonctions (emplois, commerces, habitations) et surtout un réseau de transport en commun et de mobilité douce efficient. Dans le schéma TOD (Transit Oriented Development) souvent présenté en urbanisme durable, les centres s'appuient toujours sur notre définition de départ mais cette dernière est renforcée par la notion de courte distance. Celle-ci propose des périmètres au sein desquels nous recourons plus facilement aux transports en commun ou aux modes doux. Pour renforcer encore cette mobilité dite durable, ces périmètres s'accompagnent de toute une série de fonctions et de densité.



Source R. Rogers, Partnership (1996-2000), Masterplanning London, URBAN TASK FORCE - www.rsh-p.com, consulté le 30 janvier 2009



Source: URBATOD et UQAM - 2006-2007 - http://www.urbatod.org/, consulté le 13 octobre 2008

[7] C. Moulinie et M. Naudin-Adam (1995), *Appréhender la densité, 1. repères historiques, Note rapide sur l'occupation du sol*, Paris, IAURIF (Institut d'aménagement et d'urbanisme de la région Ile-de-France), n° 382.

[8] Notons qu'un biais existe dans cette étude, lié à la proportion des locataires par rapport aux propriétaires.

[9] Collectif - Apur (Atelier parisien d'Urbanisme) (2003), *Quelle forme urbaine pour quelle densité vécue?*, Paris, Apur, n° 10.

[10] Selon la définition posée par F. Choay, un modèle se caractérise *par sa valeur exemplaire et son aspect reproductible* (F. Choay, 1965, *L'urbanisme: utopies et réalités, une anthologie*, éd. Le Seuil, Paris, p. 16). L'urbanisme durable, bien que peu théorisé et en grande partie expérimental, s'affiche surtout au travers de ses projets-pilotes, quartiers durables, reproduits et adaptés dans divers pays principalement européens.

Ainsi, les plus fortes densités bâties sont préconisées dans le périmètre central qui doit impérativement reposer sur un arrêt de transport en commun et sur toute une série de fonctions économiques, commerciales ou de services. Plus on s'éloigne du centre, plus les densités bâties diminuent et plus la fonction résidentielle est représentée. Ce schéma peut conduire à une modélisation spatiale plus polycentrique. Le territoire s'organise alors, non plus autour d'un centre principal concentrant toutes les fonctions importantes, mais autour d'une multitude de pôles connectés entre eux par un ou plusieurs réseaux de mobilité.

Densité perçue: facteurs psychologiques

Contrairement à la culture, les facteurs psychologiques ne rendent pas compte d'une identité collective qui crée un sentiment d'appartenance mais plutôt des sentiments et réactions propres à un individu. Ils varient donc suivant l'âge, les sexes, les capacités physiques des individus, les caractéristiques de l'environnement physique. Parmi ces critères, la qualité architecturale influence directement notre perception de l'espace. La vision d'un bâtiment ne nous laisse pas insensible. Il entraîne une réaction "d'attraction" ou de "répulsion" sur le passant. Le domaine est très subjectif et le sentiment provoqué varie suivant l'individu. L'appréciation des formes urbaines fait donc référence à une certaine qualité architecturale plutôt qu'à une notion de densité. Stokols en 1976[11] mettait déjà en évidence que les caractéristiques physiques d'un environnement peuvent modifier la perception de densité d'un individu. Plus récemment, l'Apur précise dans son étude: "*(...) l'habitat collectif a mauvaise presse. Il bénéficie d'une image négative et stéréotypée, renforcée par les médias. Pour rivaliser avec la maison individuelle, il doit offrir une certaine qualité architecturale valorisante pour les usagers, des logements suffisamment spacieux et modulables, enfin être associés à une richesse d'équipements et de services de proximité*"[12]. L'attraction d'un bâtiment ou d'un espace dépend essentiellement de quatre facteurs: l'échelle de l'ensemble bâti, son rythme, et deux rapports: le premier entre le bâti et son environnement construit, le second entre le bâti et le non-bâti.

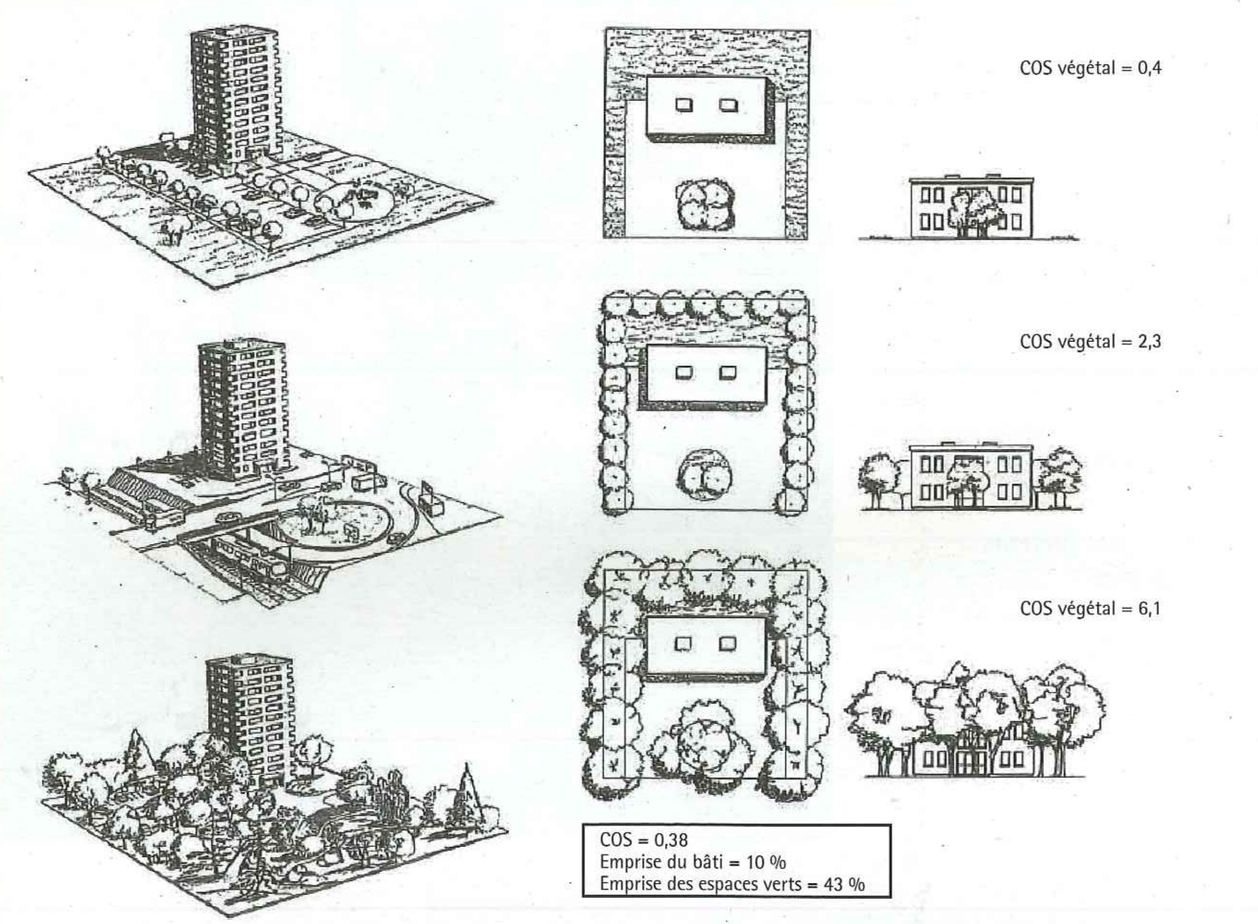
- ***L'échelle humaine*** permet de comprendre d'un regard l'espace dans lequel on se trouve. Elle établit le rapport entre un individu et son milieu en prenant comme étalon de mesure la taille même de l'individu. Une lisibilité claire de l'échelle humaine face à une composition de façade ou d'ensemble bâti facilite l'appréhension de son espace vécu. Elle est perçue comme une réaction positive. Tous les éléments pouvant servir d'étalon, afin de saisir la dimension de l'ensemble (porte, fenêtre, moulures, ...), participent à une lisibilité claire de l'échelle humaine.

- Autre facteur pour une architecture attractive, ***le rythme*** des façades ou la répétition d'éléments reconnaissables. Il s'en dégage une idée de mouvement. Le mouvement le plus naturel de l'homme étant horizontal, le rythme le plus marquant en architecture est vertical. Il participe au séquençage d'un parcours. Une façade à dominante horizontale entraîne une fuite du regard et une accélération du mouvement. Le séquençage vertical des façades d'une rue obtenu par l'utilisation de matériaux différents, par un décrochement des façades, par des éléments de construction à dominante verticale (fenêtres, descente d'eau, ...) ralentit le regard du passant. Le rythme peut présenter diverses formes: être à dominante verticale, horizontale, présenter plutôt un caractère neutre ou exceptionnel pour symboliser une fonction singulière, par exemple un palais de justice, mais, pour une lecture positive de l'espace, il faut une certaine cohérence et une certaine harmonie dans les rythmes, il faut une séquence de rue homogène.

- Dans ***la relation entre le bâti et son contexte construit***, la densité est bien perçue s'il existe un sentiment de cohérence entre les bâtiments. Ce sentiment est généralement obtenu lorsque le bâti présente une faible différence de gabarit. Un immeuble "tour" provoquera un sentiment de répulsion s'il est directement implanté à proximité d'habitation de trois niveaux en façades par exemple. Tandis que le même immeuble "tour" implanté en relation avec d'autres immeubles de gabarit similaire présentera un sentiment de cohérence.

[11] D. Stockols (1976), *The experience of crowding in primary and secondary environments, Environments and Behavior*, n° 8, pp. 49-86.

[12] Collectif - Apur (2003), id.



Source: V. Fouchier (1997), Les densités urbaines et le développement durable, le cas de l'Ile-de-France et des villes nouvelles, éd. du SGVN

- Dans ***la relation entre le bâti et le non-bâti***, il est important que le vide soit défini. En ce sens, la présence ou non de végétation est primordiale. "*Elle a, pour la majorité des citadins, une valeur affective: présence vivante dans un milieu où la matière inorganique domine. Ses couleurs tranchent avec celles de la brique et du béton, comme ses parfums avec les odeurs urbaines. Elle crée, en été, des zones d'ombre bienvenues, et nous rappelle un phénomène naturel qui aurait tendance, en ville, à s'estomper quelque peu: la succession des saisons*"[13]. Outre sa valeur affective, la végétation participe à la construction d'une échelle humaine. Le non-bâti peut être défini également par le mobilier urbain et les revêtements de sol qui offrent à l'usager une meilleure lecture de l'espace et de son appropriation possible.

Le modèle de l'urbanisme durable tient compte de ce phénomène. Comparons sept projets-pilotes généralement reconnus comme durables. Ces sites ont été sélectionnés parce qu'ils respectaient les principes de durabilité (socialement équitable, environnementalement vivable et économiquement viable) et parce qu'ils font l'objet d'une documentation foisonnante.

Pour six de ces projets, la principale source d'information est issue de *Quartiers durables, Guide d'expérience européenne* rédigé par l'ARENE. Il s'agit de: BedZED à Beddington, au Royaume-Uni, Bo01 à Malmö en Suède, Hammarby Sjöstad à Stockholm en Suède, Vesterbrö à Copenhague au Danemark, Vauban à Fribourg en Allemagne, Kronsberg à Hanovre en Allemagne. A ces projets, nous ajoutons l'analyse du quartier de Riesenfeld en Allemagne. Les informations des quartiers Riesenfeld et Vauban sont complétées par des données récoltées durant un voyage d'étude.

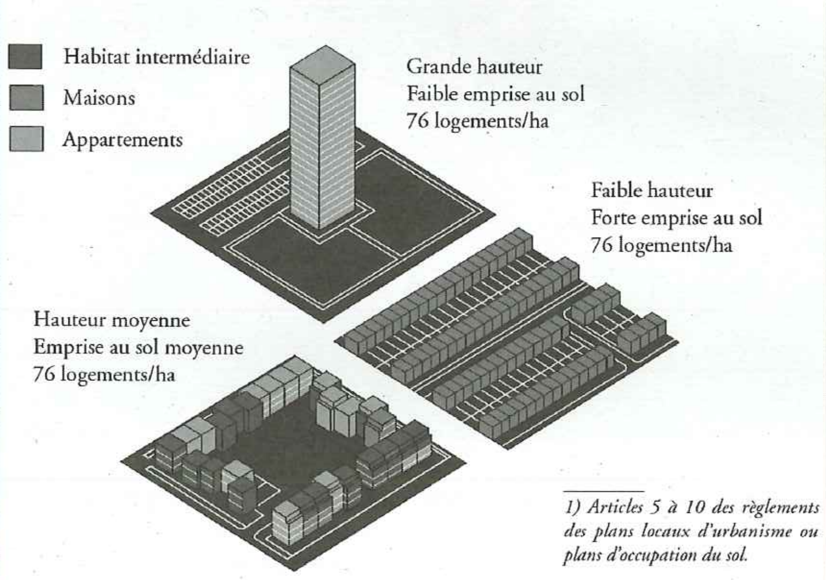
L'analyse des quartiers[14] nous montre que la densité bâtie et la densité de population sont toutes deux fort variables d'un projet à l'autre. De plus, une faible densité bâtie (nombre de logements/hectare) ne signifie pas forcément une faible densité de population (nombre d'habitants/hectare). Sans pour autant tirer des conclusions hâtives, nous pouvons tout de même affirmer que certains calculs de densité réelle varient d'un projet dit durable à l'autre. Il n'existe donc pas une règle d'or bien définie en matière de densité durable mais plutôt d'une proportion bien adaptée au contexte.

Autre élément intéressant à observer, chaque projet prône un retour à une urbanisation plus compacte et, par conséquent, à une certaine densité bâtie. Ce fait, contraire à notre culture occidentale actuelle, n'est rendu possible que par la prise en compte d'une certaine qualité de l'espace et notamment de la densité perçue. Pour faire face à l'image dévaluée des fortes densités, le modèle d'urbanisation compacte propose une forme architecturale, compromis entre la maison individuelle et l'habitat collectif. Le retour au mitoyen s'impose sans toutefois présenter des gabarits excessifs. La hauteur proposée dans ces sept projets n'excède généralement pas les cinq niveaux. Il nous faut signaler également la grande homogénéité en termes d'architecture. Au sein d'un même projet, les gabarits varient peu, de même que le rythme des façades. L'échelle humaine est toujours fortement marquée, notamment par des débords de terrasses ou une architecture qui souligne les ouvertures. Enfin, le traitement des espaces publics, en règle générale, fait l'objet d'une attention toute particulière de la part des concepteurs. La végétation y joue un rôle paysager important et participe fortement à l'acceptation de la densité. En ce sens, dans les projets de quartiers durables, la végétation est intégrée comme élément majeur pour la définition d'un cadre de vie agréable.

[13] M. Errera et B. Cassiers (1984), *Lecture de la ville*, Régie de l'agglomération de Bruxelles.

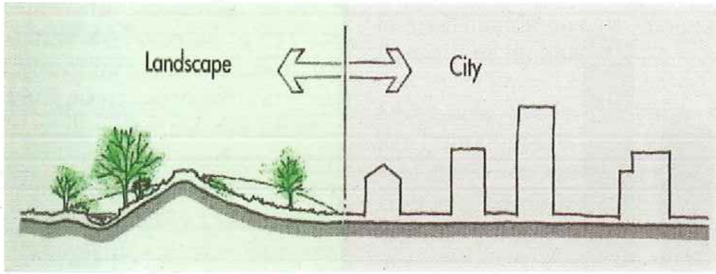
[14] ARENE (2005), *Quartiers durables, Guide d'expériences européennes*, Île-de-France, éd. IMBE, p. 7.

Modulations morphologiques de la densité

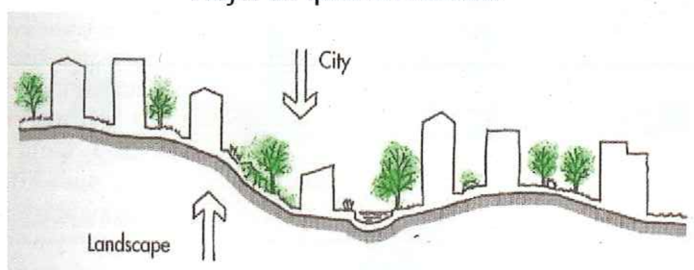


Source: C. Moulinie et M. Naudin-Adam (1995), Appréhender la densité, 2. Les indicateurs de la densité, Note rapide sur l'occupation du sol, Paris, IAURIF (Institut d'aménagement et d'urbanisme de la région Ile-de-France), n° 383.

Projet habituel d'urbanisation



Projet de quartier durable



Source: C. Von Borcke (2003), Landscape and nature in the city, T. Randall, Sustainable Design and environnemtal approach, Londres, Spon Press, p. 33.

Densité et développement durable: le retour à la ville compacte?

Avantages...

L'étalement urbain est considéré comme "*la forme "dispendieuse" de la suburbanisation (Ewing, 1997: 108), a contrario de la "ville compacte" qui permettrait certains types d'économie*"[15].

Une meilleure compacité de l'urbanisation, c'est-à-dire des ensembles bâtis plus resserrés, participe, outre à une gestion parcimonieuse du sol, à une économie de réseaux et à la création d'économies d'échelles et d'agglomération (Marshall, 1920). Pour rédiger la suite de ce chapitre, nous nous sommes inspirés de l'article de G. Pouyanne[16].

En termes d'économie, nous en dénombrons essentiellement quatre.

- *Une économie d'espace*: par essence, la compacité de l'urbanisation est moins consommatrice d'espace que l'étalement urbain. Elle permet l'économie des sols non urbanisés tels que les zones agricoles, les espaces naturels. En préservant les sols non urbanisés, elle participe à la conservation des paysages et des espaces liés à leur habitat naturel. Une certaine compacité de l'urbanisation permet donc, d'une certaine manière, une économie de coûts environnementaux.
- *Une économie de moyens*: de nombreuses études se sont penchées sur la question des coûts liés à l'urbanisation - Lacour en 1975, Richardson en 1978, Morlet 1992 et 2001, Fouchier en 1997, CPDT 2000, etc. - et, pourtant, il n'existe aucune conclusion unanime. Partant du principe que l'étalement urbain nécessite des surcoûts en terme d'infrastructure (allongement des réseaux d'égouttages, du cycle des déchets et des impétrants en règle générale), certaines études mettent en évidence le lien positif entre la

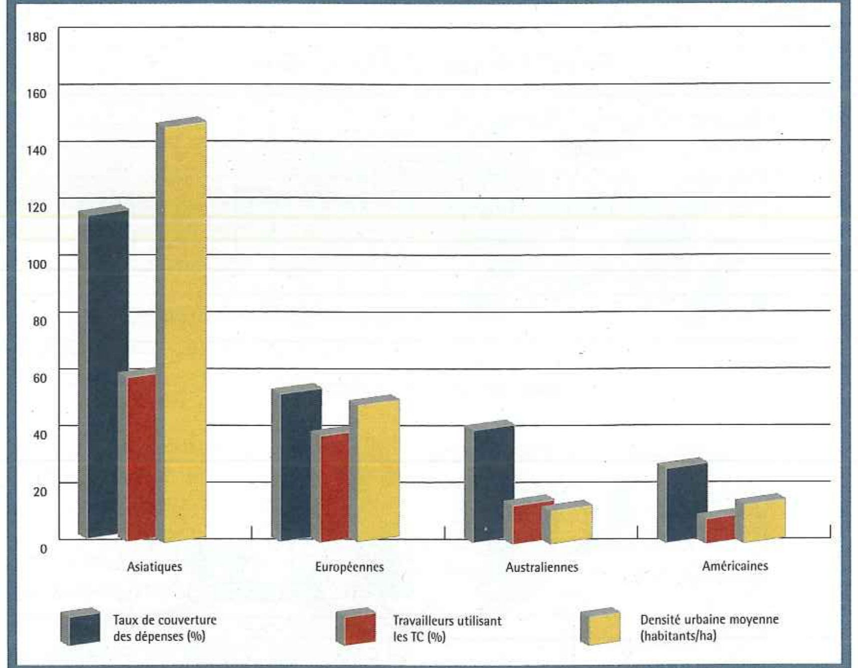
[15] G. Pouyanne (2004), *Des avantages comparatifs de la ville compacte à l'interaction forme urbaine-mobilité. Méthodologie, premiers résultats*, Les cahiers scientifiques du transport N° 45/2004, IERSO, IFReDE-GRES université Montesquieu - Bordeaux IV, p. 53.

[16] Ce texte s'inspire de G. Pouyanne. (2004), *id.*

consommation d'énergie des logements pour le chauffage et la densité (Fouchier 1997), et d'autres, que les logements individuels et collectifs datant d'après 1975 consomment autant d'énergie les uns que les autres (Morlet 2001). En termes de coût d'infrastructure, Guengant en 1992 montre qu'il n'existe pas de rapport entre densité et coûts de viabilisation de lotissements dans la banlieue de Rennes et, plus récemment, la CPDT (2000) montre que la désurbanisation entraîne des surcoûts en termes notamment d'infrastructure et d'équipement. Même si ces résultats contradictoires sont à prendre avec prudence, il semble tout de même plus souvent admis que l'étalement urbain entraîne un surcoût en termes de moyens.

- ***Une économie d'agglomération***: des activités complémentaires, voire même concurrentes, créent, par leur concentration, une certaine attractivité et génèrent un phénomène de polarisation. C'est le cas, par exemple, des quartiers ou des rues à activités spécifiques, voire des centres commerciaux. Ce principe est d'ailleurs appliqué dans certains pays pour déterminer la localisation des activités. *"Aux Pays-Bas, la politique de "l'ABC" repose sur le slogan "the right business at the right place"; une approche typologique permet d'attribuer une note (de A à C) à chaque activité, selon le nombre de salariés et de visiteurs et la dépendance au transport routier (activités de logistique par exemple). Le potentiel de mobilité de la firme déterminera un potentiel d'accessibilité et, par suite, une localisation. La densification se fait autour de noeuds d'accessibilité" (Welkers, 1997)* [17].
- ***Une économie de proximité***: une meilleure rentabilité des infrastructures. Elle permet notamment d'optimaliser les systèmes de réseau de transport en commun traditionnellement basés sur le transport de masse (train, métro, tram, bus). Emanguard (1994) met en évidence *"la relation positive entre la densité sur des variables d'efficacité telles que le coefficient de remplissage, le nombre de voyages par habitant desservi par an, le nombre de véhicule-kilomètre et la densité du réseau"*. Pareillement, Kenworthy et Laube (1999) constatent que *"plus les densités sont fortes, plus le taux de couverture des dépenses de fonctionnement des transports en commun est élevé"* [18].

Densité urbaine et efficacité des transports en commun



Source: J.R. Kenworthy et F.B. Laube (1999), Patterns of automobile dependence in cities: an international overview of key physical and economic dimensions with some implications for urban policy, transportation Research Part A., p. 33.

[17] G. Pouyanne (2004), op. cit., p. 58.

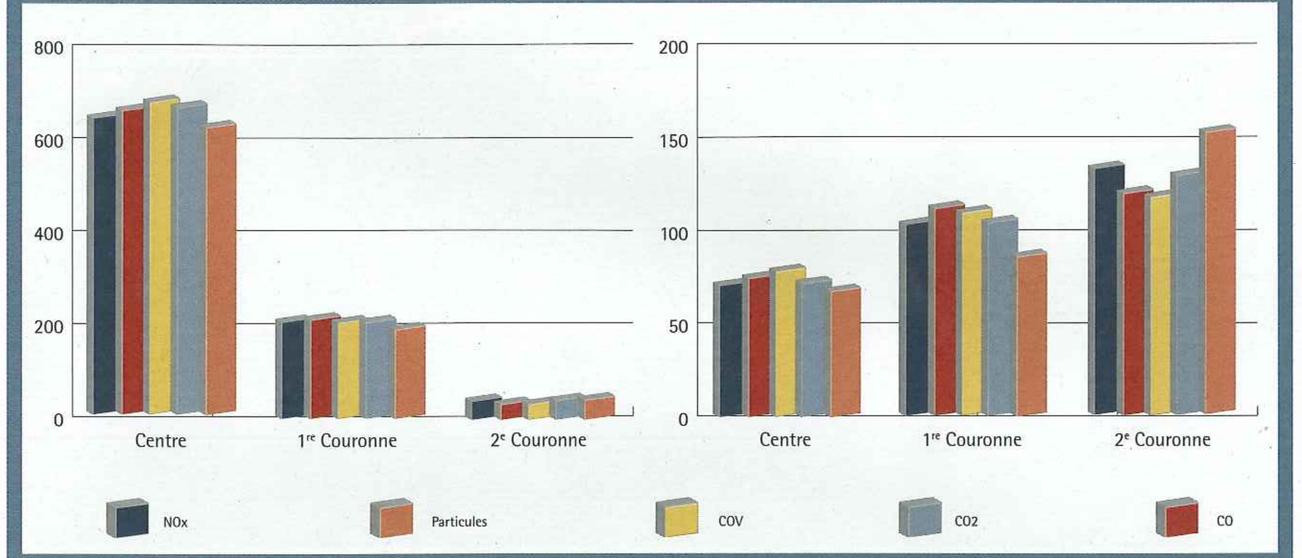
[18] G. Pouyanne (2004), id., p. 57.

... et inconvénients

Densifier de manière raisonnée suggère un respect environnemental, social et économique. La densification favorise une meilleure rentabilité des infrastructures, telles que les centres sportifs, transports en commun, commerces, ... Elle participe à une utilisation réfléchie de l'espace urbain. A contrario, une densification inadaptée peut conduire à des inconvénients non négligeables: concentration des nuisances, engorgement, surcoût technique, ...

La densification présente un risque d'augmentation de la congestion. En augmentant la congestion, la compacité urbaine concentre également les nuisances. Or, les habitants des centres qui produisent pourtant moins de polluants que les habitants péri-urbains en subissent plus les effets.

Taux d'émission au m² | Taux d'émission/résident/jour



Source: Densité d'émissions polluantes et émissions par tête, selon la distance au centre à Lyon, source Nicolas et alii (2003), G. Pouyanne, Des avantages comparatifs de la ville compacte à l'interaction forme urbaine-mobilité. Méthodologie, premiers résultats, Les cahiers scientifiques du transport, N° 45/2004, 2004, IERSO, IFReDE-GRES université Montesquieu – Bordeaux. IV

La densification risque d'augmenter la ségrégation sociale. La compacité de l'urbanisation réduit l'espace disponible à la construction. Elle influe donc d'une certaine manière sur le prix du foncier. En ce sens, on risque de voir les moins fortunés exclus des centres-villes.

"Cette inflation pourrait, si elle est complétée comme c'est le cas aujourd'hui de mesures de renouvellement urbain et de requalification du centre-ville, aboutir à une accélération du mouvement de gentrification déjà sensible depuis les années 1980" (Bradway Laska, Spain, 1980). *"On peut craindre que ces évolutions n'aboutissent à une forme en "beignet", ou plus précisément en anneau (donut), où le centre ancien, réservé aux classes riches, est bordé par l'habitat des classes défavorisées"* (Smyth, 1996). *"Ce risque peut même aller jusqu'à une "muséification" du centre-ville où le patrimoine bâti, extrêmement valorisé, est principalement dédié aux touristes et à l'habitat des classes les plus riches"* [19].

Enfin, suivant la définition du terme densité que nous avons posée au début du chapitre, il nous faut tenir compte tant des aspects qualitatifs (la densité réelle) que des aspects quantitatifs (la densité perçue). Dans la conscience collective actuelle, la qualité de vie en termes d'urbanisation passe principalement par la maison-type "quatre façades" avec jardin. Une image bien loin de l'habitation plus "compacte" de l'urbanisme durable.

Selon une étude française menée par l'Observatoire de la ville en janvier 2007, *"lorsqu'on demande aux Français, parmi les sept types d'habitation qui leur sont proposés, celui dans lequel ils souhaiteraient habiter, c'est la maison individuelle isolée qui remporte le plus de suffrages: un peu plus d'un Français sur deux (56 %). Vient ensuite la maison individuelle dans un ensemble pavillonnaire (20 % des répondants) et le petit habitat individuel en ville (11 %). A des niveaux de citations moindres, on trouve l'habitat haussmannien (5 %), le petit/moyen habitat collectif en ville (3 %), les grands ensembles d'habitat collectif de tours et de barres (1 %) et le grand immeuble (1 %)"* [20].

La compacité de l'urbanisation risque d'imposer un principe, au premier abord, à l'encontre des aspirations des habitants.

En termes de densité, il est primordial de respecter un juste équilibre. L'étalement urbain nous pose certes des problèmes en termes de durabilité, mais une densification extrême aussi. A partir de certaines valeurs seuils, la compacité a des effets négatifs non durables. Ces valeurs sont parfois difficiles à établir, notamment dans le cadre de la densité perçue qui repose sur des impressions personnelles et culturelles. Dès à présent, on peut supposer que les calculs de densité ne peuvent être considérés comme des facteurs isolés. Ils ne sont pas garants à eux seuls d'un développement durable des espaces publics. La densité doit être analysée et appréciée en corrélation avec d'autres domaines.

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[19] G. Pouyanne, op. cit., p. 62.

[20] Observatoire de la ville (2007), *Les français et leur habitat - Perception de la densité et des formes d'habitat*, principaux enseignements du sondage réalisé pour l'Observatoire de la ville du 10 au 12.1.2007, p. 2.

THE APPLICATION OF SOUNDSCAPE APPROACH IN THE DEVELOPMENT OF SUSTAINABLE URBAN PUBLIC SPACES

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Abstract: Design and renovation of urban public areas is one of the important issues in development of European cities. Typically, broad variety of approaches (sociological, ecological, environmental, physical etc) is needed. Earlier studies show the necessity of the transversal multi-disciplinary approach for development of sustainable cities. In order to study the acoustical dimension of this issue, the concept of soundscape needs to be proposed and elaborated. Soundscape approach differs from the classical statistical noise analysis in the evaluation of a context-related noise and in the extrapolation of environmental sounds in its complexity and ambivalence. This article will propose a method for acoustical characterization of an urban area in the framework of the Belgian federal project: SD/TA/05A Design and renovation of urban public spaces towards sustainable cities (DRUPSSuC).

Keywords: soundscape, sustainable development of urban public areas

1. INTRODUCTION

Just like landscapes are encompassing most of the visual aspects of an environment, the term 'soundscape' is used as a complex unifying term to merge the acoustical aspects called also as an 'environment created by sound'. The word 'Soundscape' was for the first time introduced by Murray Schafer in the year 1977 to denote an auditory equivalent to visual landscape.

In view of designing sustainable urban environments, an important question is how to design a soundscape, suitable for a given cityscape. The latter one is determined by urban engineers, architects, and by economical (business development) and sociological (e.g. population settlement) evolutions, which is not always possible to control or even predict. Along with these evolutions, also the soundscape evolves in a spontaneous way. Nevertheless, urban design and legislation can act in a steering way to keep sufficient harmony between the expectations from the 'users' of the urban environment, and the actual soundscape.

In this term, soundscape acts as a mediator between humans, their activities and their environment and can be described as an environment of certain sound sources and the way people feel about those sounds contributing to the identity of urban areas. This approach is based on qualitative, but also quantitative aspects in combination of perception of sound and its evaluation, while combining human judgment and physical factors. Following the soundscape design methods, we would like to rethink the evaluation of the context-related noise and noise effect and the exploration of noise in its complexity and ambivalence in the concept of 'sound ambient environments'.

2. CONCEPT OF SOUND AMBIENT ENVIRONMENTS

For ten years Soundscape has been an issue in the area of community noise, but a generally-accepted soundscape approach has so far not been established. (B.Brooks 2006). In our research, we would like to concentrate on the development of the concept, based on Sound ambient environments (SAE) approach, which integrates the

(1) physical descriptions of sound, e.g. object-centered description and

(2) subjective effects of sound, e.g. subject-centered description at a cognitive and emotional level within a given community.

2.1. Object-centered description

Main objective in this paragraph is related to the reliable analysis of sound samples, by using the physical descriptions of noise, such a statistical analysis based on monitoring of the acoustical situation in the reference urban area and analysis of the sound with a respect to the psychoacoustical criteria.

Advantages of these methods are in the possibility of a collection of the exact data for an overview in the chosen urban place. By placing recording devices in the reference point, measurements can be done for hours, days and weeks and chosen urban place can be monitored during a relatively longer period. Following analysis is proposed:

2.1.1. Statistical analysis of noise

Analysis of the noise by using statistical methods, such a calculation of equivalent levels of noise L_{Aeq} [dB], or other parameters such a L_1 [dB] , L_{10}, L_{50}, L_{90} [dB] will give a good overview about the situation in an urban area. These values can be easily used for comparisons with other places.

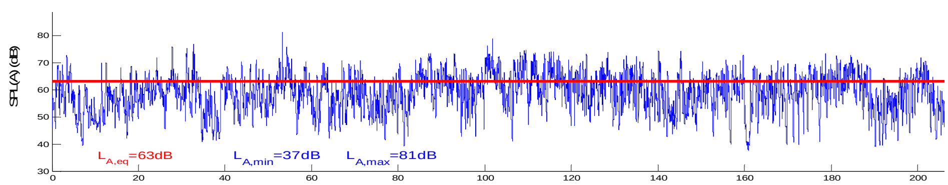

Fig.1 Sound pressure level in the time domain

2.1.2. Analysis of the spectral content of noise and its temporal structure

Nowadays computers allows real-time computation of Fourier spectra FFT or spectra in 1/3 octave bands, which deliver good first overview about the spectral components in the evaluated sound

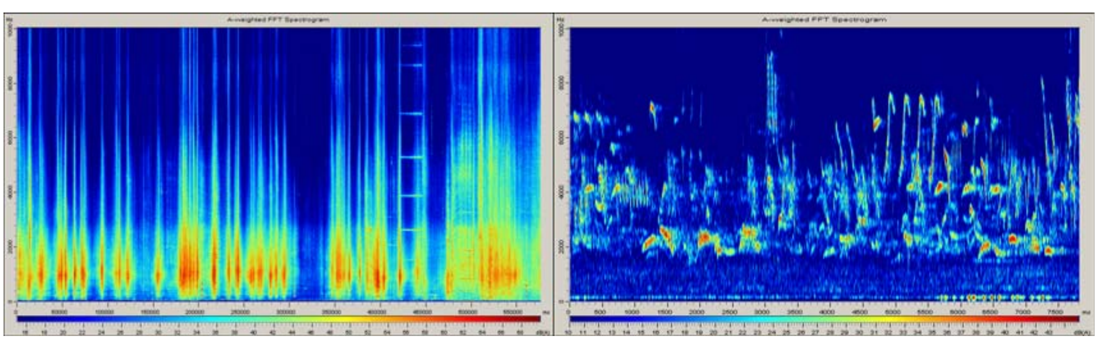

Fig.1 Analysis of the spectral content of noise by using FFT

2.1.3. Psychoacoustical analysis

Here, the analysis of sound according the psychoacoustical parameters (such Zwicker's loudness, Sharpness, Roughness, Prominence, Tonality,) will be done and compared with subjective perception in laboratory listening tests.

2.2. Subject-centered description

Subject-centered description of sound will be based on the analysis of the questionnaires in situ and results from listening tests in the laboratory. Following methods are proposed:

2.2.1 Hedonic and numerical analysis of reference urban places

Expectations of people about the sound in the urban place can strongly vary according to the person of interest and his or her activity. This activity and related expectations can vary according to the time of the day, week, season or period of the life. Different people might evaluate the same place differently. It depends on their reason to be in the area, on their mood, but mainly on their expectations. It can make difference if person visits urban place after tiring working day or on Saturday evening with expectation of somehow noisier evening.

One of our goals is therefore to get the information about the Soundscape expectation of different users, who can be:

1./ people permanently living in the reference urban area (for a long time)
2./ people staying in the reference urban area for certain period (e.g. students, etc.)
3./ people visiting the reference urban area for a short time (tourists)
4./ people passing the reference urban area for certain reason (on their way to work, etc)

People often find place pleasant if they find there fulfillment of their expectation.
Here, one of the main objectives will be the task related in looking for similarities and contradictions in the answers of different users. Main question and the most difficult question will be related to the decision “for who” should be the city designed. Averaging the opinions might be tricky and can lead to design of a place that nobody really likes.
The main objective is thus a complex analysis of human expectation in different urban public places leading to the proposal in design and renovation.

Here, the main task will be to put answers in the context with other, non-acoustical parameters. Psychology and psycholinguistics helps to find out how people give meaning to urban soundscapes on the basis of their everyday experiences and how individual assessments are conveyed through language as collective expressions.

2.2.2 Description of the Soundscape by set of acoustical numbers in the semantic and semiotic way

Nowadays, even by using recently developed sophisticated acoustical and psycho-acoustical measurable and quantifiable parameters, it still remains difficult to grasp the complete meaning of a soundscape in words only or by numbers only. Our hypothesis is that the description of the soundscape might be successfully done by combination of acoustical numbers and words:

Our proposed categories:

1./ Keynote Sounds

“The keynote sounds may not always be heard consciously, but they “outline the character of the people living there” (Schafer) Keynotes are created by nature or by permanently present sound sources. It is a kind of amorphous sound.

2./ The Sound Signals

These are foreground sounds, listened consciously, such a warning devices, bells, whistles, horns, sirens, etc. We can identify and localize these kinds of sound events.

3./ The Soundmark

A soundmark is a sound which is unique to an area. “Once a Soundmark has been identified, it deserves to be protected, for soundmarks make the acoustic life of a community unique” (Schafer).

4./ The Color

The “color of the urban area” is related to the timbre of the sound, to its frequency components and overall spectral perception.

5./ The Rhythm

The rhythm of an Urban area is determined by the rhythm of nature (changing day and night, or seasons in the year), but also by traffic jam events and quiet period or by trucks for garbage removal etc. Some cities we perceive slow and some fast.

6./ The Harmony

This depends on our acoustical expectation, such in the street with traffic lights we expect cars breaking and in the square with café's we will expect people talking while having a drink.

3. SUMARISATION AND CONCLUSIONS

The soundscape of even a well defined cityscape location is a strongly varying phenomenon, and coincidental fluctuations can make the situation strongly deviating from the average during a long time, or actually make it impossible to define an average situation. However, in a pragmatical approach, it is safe to assume that optimizing the average soundscape within it's an acoustical situation, and taking measures to limit possible strong fluctuations will always be beneficial. Solutions will be found in the improvement of the urban places based on the result of our research.

It is very obvious, that we don't want to deliver silence everywhere and so to restrict ourselves to noise reduction problem. We like to discover what the human feeling of pleasantness or annoyance depends on and to use this knowledge in the design and renovation. People need different soundscape in different situations.

We like to keep the diversity in urban areas, since we don't want to make all cities sound the same. We'd like to make urban places sound pleasant by not disturbing their typical features. People are different and it is important to give chance to everyone to find his/her favorite place to live, to rest and to work. Traffic belongs to civilization and to the soundscape of the cities in 21st century as well, so we can't forbid cars in the cities as we can't forbid insects flying in the meadows.

We don't want to find an ideal soundscape, but we like to find what people like and why by collaboration on a multidisciplinary level.

Summarization of the knowledge will lead to proposal for design and renovation of urban public places.

ACKNOWLEDGEMENTS

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An important issue in the development of European cities is the design and renovation of the urban public areas. Typically, a broad variety of approaches (sociological, ecological, environmental, physical, etc.) is needed and earlier studies have shown the necessity of the transversal multi-disciplinary approach in this issue. In order to study the acoustical dimension, the concept of soundscape needs to be proposed and elaborated. The soundscape approach differs from the classical statistical noise analysis in the evaluation of a context-related noise and in the extrapolation of environmental sounds in its complexity. Nowadays, even by using recently developed sophisticated acoustical and psycho-acoustical measurable and quantifiable parameters, it still remains difficult to grasp the complete meaning of a soundscape in words only or by numbers only. Our hypothesis is that the description of the city soundscape might be successfully done by combination of acoustical numbers and words.

1 Introduction

In view of designing sustainable urban environments, an important question is how to design a soundscape, suitable for a given cityscape. The latter one is determined by urban engineers, architects, and by economical (business development) and sociological (e.g. population settlement) evolutions, which is not always possible to control or even predict. Along with these evolutions, the soundscape evolves in a spontaneous way. In many cases we therefore speak more about the soundscape description and evaluation, than about the soundscape design as such.

Most of the existing studies done in large urban or rural areas were in the past based on noise measurements (e.g. quantitative description) and noise propagation [2, 3]. Measurement of noise is rather straightforward due to its clear definition and its impact on human health has been investigated in terms of auditory and non-auditory effects. [4-6] Therefore, if we plan to evaluate an urban area, the measurements of noise should never be omitted. Series of noise regulations have been already established and the noise maps in many EU countries have been prepared. [7]

In the seventies, a new approach to the sonic environment including the qualitative assessment of urban areas was introduced and developed through the soundscape description. [8] Several authors have shown the masking effect of sound as an important factor in creating the satisfactory acoustical conditions. Some studies have even concluded that because of this reason (i.e. masking effect), the reduction of noise levels not always contribute to global acoustical comfort. [9, 10, 11].

The recent research shows the importance of multidisciplinary approach to this topic. Several authors compare statistical values of sound pressure level (such L_{90}, L_{50} L_{10} or L_{Aeq}) with results based on number of interviews in situ. In the work of Yang and Kang [9] it has been concluded that the background sound levels act as an important quantity in evaluation of urban public spaces. Further, it has been also confirmed that the acoustical comfort perception is more affected by the character of the sound source than by its general sound level.

Numerous studies have been performed with a special attention to rural quiet areas by looking for a multi-criterion assessment based on a set of carefully chosen indicators, suitable for the development of the categorization and quality labels. [12, 13] Acoustical comfort in residential areas has been also separately investigated and evaluated by many authors and can be found in the literature. [14, 15]

However, the description of the soundscape needs not only the acoustical numbers, but also semantic data. It is often necessary to look at the context of the noise instead of just simply evaluating it by different acoustical quantities. In the research of Dubois [16], the cognitive categories related to description of soundscapes were considered while comparing the individual experiences of people and collective representations shared in the language of society.

Some other works deal with the acoustic similarity of soundscapes and its identification by the multidimensional tool called "dualistic psychoacoustic strategy" [17] This tool is based on the collection of all available and detailed acoustic information that may be picked up by human perceptual system when listening to a complex sonic situation. However, the research on neural network models still needs further development.

One of the most important questions related to the sonic environment evaluation is "how to collect the reliable data". The fast evaluation of streets, squares and parks can be sometimes based on recordings of the binaural sound, while walking through the city. [18] So called "Soundwalk method" allows us to collect the information along the streets instead of just placing one or few measuring points on fixed positions.

Dealing with the development of sustainable cities, a comparison of the acoustical situation in the past and present with a prediction of the future sonic conditions might be appealing. Since the technology of high quality sound recording is rather new, the information about the acoustical situation in the past can be found only in the literature, contemporary paintings, photographic material or other accessible historical sources. Some research has been already done in this way [19].

2 Description of our research context

Acoustical research is done in the framework of the multidisciplinary project, which deals with the development and renovation of urban public places in Belgium. This research carries many transversal activities between several research fields such as sociology, microclimate and windcomfort, density, mobility, vegetation and biodiversity. Due to the complexity of the project, optimal (simple and fast) method for the evaluation of different urban places is needed. We are aware of the importance of the acoustical details in soundscape description and about the danger of too much simplification. Nowadays, even by using the recently developed sophisticated acoustical and psychoacoustical measurable and quantifiable parameters, it still remains difficult to grasp the complete meaning of a soundscape in words only or by numbers only. Our hypothesis is that the description of the soundscape might be successfully done by combination of acoustical numbers and words.

3 Development of methodology

To have a complex view on each particular soundscape, we try to work on two basic levels: (1) **Noise evaluation (NE)** based on known noise maps and our own recordings in situ and (2) **Qualitative assessment (QA)** partially on "hard" data of binaural acoustical recordings and "soft" data with respect to the context of the sound and to people's perception.

On the first level (i.e. NE), the impact of noise on human health is the priority, whereas the second level (i.e. QA) is about the human appreciation of the soundscape based on perception, evaluation and expectation. This leads us to start with description of the sonic environment not only by acoustical numbers or by semantic description, but by including of both types of data.

Strictly speaking, the collection of our acoustical data is based on binaural recordings in the chosen streets, squares and parks in the city centers, urban and suburban areas where we try to collect as much data as possible by performing the so called "soundwalks". For each recording we make a picture and we keep the information about the day, time, weather conditions, etc. By having the original material stored in the binaural wave format, listening tests or new post-processing algorithm (such as changing of the integration time or development of new variable) can be done later on if necessary.

Acoustical recordings are accompanied by the interviews as well. Following the principles of grounded theory we try to avoid pre-conceptualization. We use our knowledge and literature sources only to formulate some "hints" or "sensitizing concepts" which are intended to facilitate the research process. However, at the same time we want to be open for potential discoveries. Grounded theory methodology serves here as a tool for investigating a phenomenon "in itself", which means that neither "right theoretical framework", nor "right answers" will be imposed. The concepts and hypotheses are rather developed during the research process than tested or borrowed from other theories.

3.1 Noise evaluation

The noise evaluation is considered at first and it consists of the known statistical analysis based on monitoring of the acoustical situation in the reference urban area. The analysis of noise by using statistical methods, such as calculation of the equivalent levels of noise L_{Aeq} [dB], L_{den} or other parameters such a L_5 [dB] , L_{10}, L_{50}, L_{95} [dB] gives a good overview about the noise situation in an urban area.In this part, our measurements will be calibrated with general noise maps accessible for a given region and the precision of measurements will be estimated.

In this part, our measurements will be calibrated with a general noise maps accessible for given region and precision of the measurements will be estimated

3.2 Qualitative assessment of "hard" acoustical data

We presume that the perceived acoustical comfort of a given soundscape is mainly influenced by human expectation. This presumption encourages us to look for common features of similar environments, such as shopping streets with or without traffic; residential streets with family houses or high blocks of flats; parks in the city center or in the suburbs, etc.

Commonly used or standardized quantities for qualitative assessment of urban public places have not been established so far. Several authors use known psychoacoustical parameters originally developed for the evaluation of stationary sound sources. [18, 21] However, urban soundscape usually consist of a mixture of several sounds with different intensities, directivities and durations. This makes the evaluation more difficult mainly in choosing the integration time during the calculation of the psychoacoustical parameters.

3.2.1 Psychoacoustical analysis

A part of our analysis is based on the estimation of Loudness N [son], Sharpness S [acum], Roughness R [cAsper] and Fluctuation strength F [cVacil] in time domain followed by the calculation of statistical values, expressed as value of the parameter (L, N, R, S or F) exceeded in x % of time.

Global analysis of all measured places helps us to understand the behavior of the psychoacoustical parameters in the urban public places particularly. It can be seen, that the distribution of statistical values is different in case of each variable. Fig.1 left shows the statistical values of loudness (N_1, N_2, …, N_{99}, N_{100}) based on 50 recordings of a duration 10–15 minutes/per recording in several streets in Leuven. Fig.1 right shows the same data for Sharpness, etc.

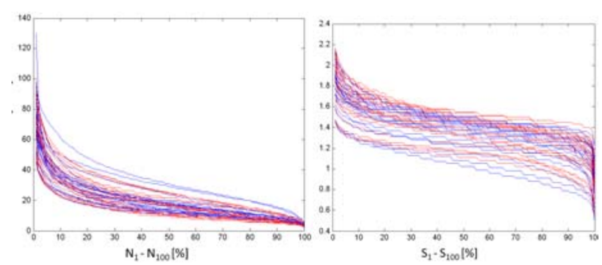

Fig.1. Statistical values of Loudness (left), and Sharpness (right)

To be able to decide about good descriptors, the maximal differences in soundscape within one place and the maximal differences between all the evaluated places concerning all chosen parameters have to be estimated and the character of the distribution has to be considered.

Figures 1 shows the distribution of the statistical values. The background noise in the streets defined by N_{95} fluctuates less from place to place than the peak values defined by N_5. We can conclude that it would not be very convenient to work only with average values N_{50}. On the other hand, statistical values of sharpness based on measurements in urban public spaces have rather normal distribution and so it will probably allow us to work only with average sharpness values S_{50} in the future. The histograms of fluctuation strength and roughness are not included in this text due to the page limitation, but they also confirm that the average values F_{50} and R_{50} would not contribute as a sufficient quantity in the final set of descriptors

3.2.2 Parameters related to the binaural aspects of hearing

In previous studies about the acoustical comfort description, it has been shown that the perception of a person's envelopment by sound sources and the ability to distinguish and localize the disturbing or pleasant sound sources influences the global perception of acoustical comfort. For this reason we try to involve the binaural aspect of hearing in the assessment of the urban soundscape, too. The perception of envelopment as well as the ability to localize sound sources is thanks to binaural cues and monaural cues encompassed in the Head-related transfer function (HRTF). However, the involvement of full HRTF in the urban soundscape context would be too complicated and probably not completely useful, since the monaural cues are too individual, due to the differences in the shape of the human ear and upper body. On the other hand, the binaural cues are more general and can be described by the interaural time difference (ITD) and interaural level difference (ILD). It is known that due to the shape of the human head, ILD is more pronounced in frequencies above 1.5kHz, and ITD in low frequencies. [20]

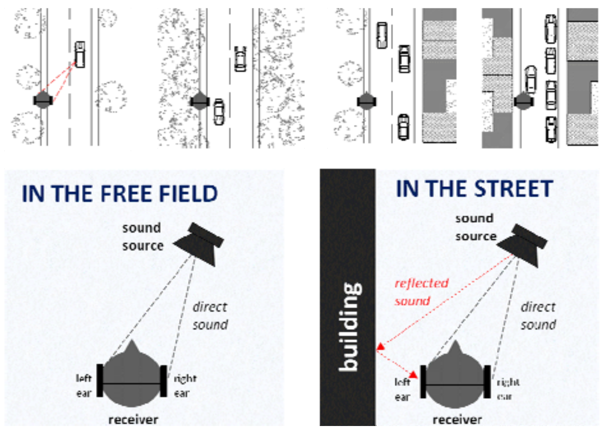

Fig.2. Principe of the "*uILD* number".

In our research, the development of the parameter called "urban interaural level difference" (*uILD*) is in progress. This parameter is based on the comparison of the acoustical situation in the left ear and right ear with respect to the level difference. Proposed "*uILD* number" $uILD_1$ and $uILD_2$ are defined as:

$$uILD_1 = \frac{\sum_{i=1}^{n}(L_{Li} - L_{Ri})}{n} \quad [\mathrm{dB}] \qquad (1)$$

$$uILD_2 = \sum_{i=1}^{n}\sqrt{\frac{(L_{Li} - L_{Ri})^2}{n}} \quad [\mathrm{dB}] \qquad (2)$$

where X_{Li} is a value of the acoustical parameter (*L*, *N*, *R*, *S* or *F*) in the left channel in the time *i*. X_{Pi} is a value of the acoustical parameter (*L*, *N*, *R*, *S* or *F*) in the left channel in the time *i* and *n* is the number of the values. Binaurality is checked for the psychoacoustical parameters *N*, *R*, *S* and *F* and is defined as *uIND*, *uIRD*, *uISD* and *uIFD* in the same way as $uILD_1$ and $uILD_2$.

The proposed parameter $uILD_1$ should show, which ear (left or right) was most of the time exposed to higher sound levels, sharpness values, etc. The $uILD_2$ gives information about the surrounding of a person by sources in general and it is less sensitive on turning of the head during the recordings.

3.2.3 An example of the case study: street assessment by the "hard" acoustical data analysis

Our case study street, Bondgenotenlaan in Leuven, is one of the main shopping streets in the city center. This street connects the railway station with the main square in the town and it is 1 km long. The traffic, such as cars and busses, makes this street well accessible, but it is also a source of noise. The acoustical situation in this street depends on the day of the week and the hour during the day. Since the peak hours of shopping are on Saturdays and on the week days between 17-18, when people return from work and still go shopping or they leave the city center by car or other transportation.

Seven binaural recordings have been performed by using the so called "Soundwalk" method.

Analysis of the statistical values was done with a respect to the calculation of L_A and 4 psychoacoustical parameters (*N*, *R*, *S* and *F*). For this article, results of the L_A, *S* and *F* were chosen and are given in the figures 3-5.

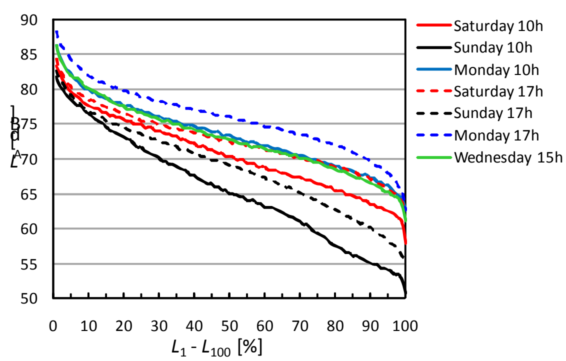

Fig.3. Comparison of the statistical values $L_1 - L_{100}$

Figure 3 shows that the peak levels don't differ so much as the values of L_{95}. This is probably caused by the busses regularly passing this street during the whole week. Frequency of the busses passing in the week days (Monday and Wednesday) is higher in comparison with the weekend, what is confirmed by the values of L_5. From the figure 5 we can also conclude, that the noise situation in this street is nearly identical on Wednesday at 15h, Monday at 10h. Average noise situation defined by L_{50} and background noise situation given by value L_{95} on Saturday at 17h is also very similar to Wednesday at 15h and Monday at 10h.

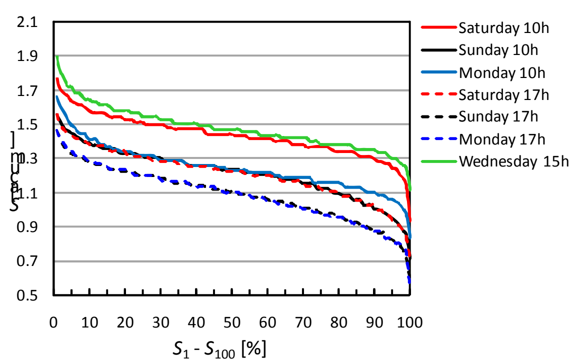

Fig.4. Comparison of the statistical values $S_1 - S_{100}$

The peak values on Saturday are statistically the same at 10h and 17h. Overall level of noise is significantly lower on Sunday morning, however the peak levels are similar to the situation on Saturday. This is probably due to the fact that the shops are closed and there are not many people in the street, but the busses are still passing in their regular times. Figure 4 shows the increase of the average sharpness on Saturday morning and Wednesday at 15h. Taking to account the levels in this days we can presume that on Sunday the increase of sharpness in sound is cause due to the overall lower levels of noise and thus the sounds with higher frequency spectra are not masked anymore by wideband noise. Higher values of Sharpness on Wednesday early afternoon is probably cause by some strong high frequency components in the overall sound spectrum what this might contribute to acoustical discomfort. Sharpness values on Monday afternoon are very low, since they are masked by other sounds with high intensities.

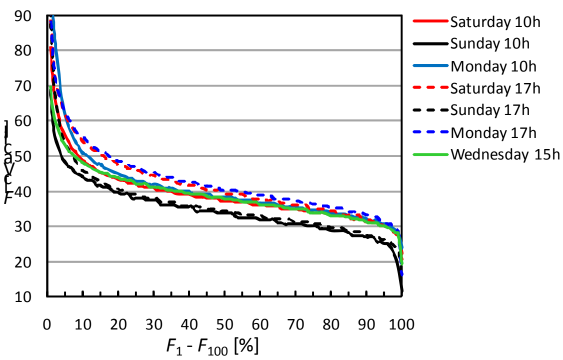

Fig.5. Comparison of the statistical values $F_1 – F_{100}$

Fluctuation strength usually reacts on sounds with short duration such as a hand clap, hammer sound or closing of the car door, but also to human voices. These kinds of sound often carry high amount of the acoustical energy accumulated in simple pulse and so they are often found in the sound level analysis as well. The average fluctuation strength F_{50} = ca 40 cVacil was in our case study highest on Monday and Saturday afternoon due to the sounds produced by people passing, talking, stepping etc. Lowest average values of about 35 cVacil were observed in the both recordings from Sunday. These differences are even more pronounced in the maximal values of fluctuation strength where the difference in F_2 is about 30 cVacil.

Analysis based on binaural parameters

In this paper, the results of three binaural parameters, *uILD, uISD*, and *uIFD* are shown. Parameter $uILD_1$ is given in the Figure 8 (in the left set of seven bars) and shows overall higher levels of sound in the left ear then in the right one. This means that the person with the binaural microphone probably walked on the right side of the road, since the road should be logically the main source of the noise in this street. $uILD_2$ given in the Figure 6 (in the right set of seven bars) shows that there is still relatively large amount of sound coming to the right ear, since the differences given by $uILD_2$ are higher than $uILD_1$. This might be caused by the reflections from surrounding buildings but also by the sound sources on the right side of the person, such as music from the shops or windows, or speech produced by people in the street. However, this can’t be decided based on $uILD_1$ and $uILD_2$ only.

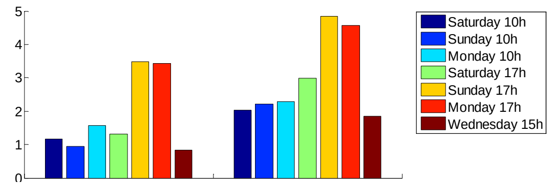

Fig.6. Values of the $uILD_1$ (1st set of 7 bars), and $uILD_2$ (2nd set of 7 bars) calculated based on 7 recordings in the reference street during 7 different days and times in the day

The $uISD_1$ values are relatively low, but they show the overall sharpness on Sunday higher in the right ear. The $uIFD_1$ values are highest on Sunday afternoon and the prevailing direction of the sound with high F values is coming from the road. We presume that this is caused not only by passing busses, but also by passing scooters and old bicycles producing high values of F in general, and by students talking to each other while driving bikes, while these sounds are not masked by other sounds.

3.3 Qualitative assessment of the “soft” data

To express the context of the sound by numbers is at the moment not completely possible. Within our project we therefore start with proposing a few categories, which will be described by words during the evaluation of the public place.

3.3.1 Proposed categories

1./ Keynote Sounds, defined by Schaffer as those, which “may not always be heard consciously, but they outline the character of the people living there”. Keynotes are created by nature or by permanently present sound sources. It is a kind of amorphous sound, in many cases sound perceived subconsciously as a background sound.

2./ The Sound Signals, understood as foreground sounds, listened consciously, such a warning devices, bells, whistles, horns, sirens, etc. We can identify and localize these kinds of sound events.

3./ The Soundmark, as a sound which is unique to an area. “Once a Soundmark has been identified, it deserves to be protected, for soundmarks make the acoustic life of a community unique” (Schafer).

4./ The Rhythm. An urban area is determined by the rhythm of nature (changing day and night, or seasons in the year), but also by traffic jam events and quiet period or by trucks for garbage removal, etc. Some cities can be perceived slow and some fast.

5./ The Harmony can be understood as overall acoustical comfort which depends on our acoustical expectation, such in the street with traffic lights we expect cars breaking and in the square with café’s we will expect people talking while having a drink.

3.3.2 Example of the city park assessment by using the “soft” data analysis.

For this case study was chosen Kasteelpark Arenberg in Leuven, Belgium. This area has a characteristic **keynote sound** produced by students driving old bikes during the whole year and by singing birds 10 month per year. Nearby the Kasteelpark is a railway station Oud Heverlee which contributes to the observed area by its **sound signals** such a ring while the closing of the ramp. Bells of the castle produce a melody which becomes a **soundmark** of this area and it is unique for this place. **Rhythm** of this urban place is caused by Soundmark repeated every 30 minutes and by sound signals in the parts of the park close to the railway station several times per hour. **Harmony** of this place is by most of the people perceived as a place with acoustical comfort. However final answer will be given after the sociological research in this place will be finished.

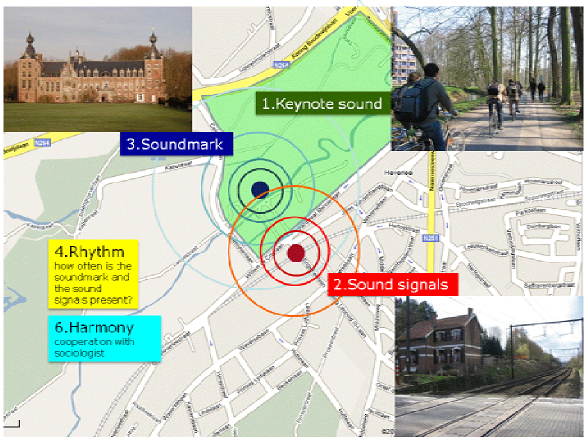

Fig.7. Example of the subject-related analysis

4 Conclusion

Soundscape of even a well defined cityscape location is a strongly varying phenomenon, and coincidental fluctuations can make the situation strongly deviating from the average during a long time, or actually make it impossible to define an average situation. However, in the pragmatical approach, it is safe to assume that optimizing the average soundscape within its acoustical situation, and taking measures to limit possible strong fluctuations will always be beneficial. Solutions will be found in the improvement of the urban places based on the results of our research.

First results, based on few examples from which two were presented in this paper, have shown the possibility to use our methodology for the description of some acoustical features of the given cityscapes. Future steps will be oriented to detailed statistical analysis of the acoustical data. It will be combined with the discovery what the human feeling of pleasantness or annoyance depends on and how to use this knowledge in the design and renovation will need comparison of the measured acoustical data with sociological investigations.

Acknowledgments

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Determination of the context related sound level in an urban public place by using a sound-masking procedure

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Introduction

In an urban environment, a multitude of sounds from cars, motorcycles, bicycles, talking people on the terraces, sound from church's bell, foaming fountain, singing birds and many others, affect soundscape. A person often becomes aware of the presence of a particular sound source if it is related to the instantaneous mental activity, or if the sound has some very remarkable feature. Once someone's attention is focused to an individual sound in a mixture, it becomes possible to qualitatively estimate its sound pressure level. Since the dynamic range of sounds occurring in daily situations is very large, very often weak sounds are masked by louder ones. However, the severeness of masking of a particular sound of interest (from here on referred to as the "signal" sound), by the other sounds in a mixture (from here on referred to as the "masking" sound), is not only determined by its relative loudness, i.e. the difference in overall "signal" sound level and in masking due to suitable frequency spectum. People are able to exploit particular spectral and temporal features of weak signal sounds to detect their presence and nature in the presence of a louder background if they understand the meaning or context of the sound signal. Boubezari and Coelho (2008) have made some steps to unravel and quantify this ability, by performing listening tests where first the threshold of people hearing a signal in white noise was determined by presenting the signal at decreasing levels till it was not heard anymore. The authors found that their result to be consistent with experiments of Zwicker & Schaft (1965), i.e. a complex sound is totally masked by a white noise equal to the level of its loudest frequency component. The sound level (SPL) of that white noise was referred to as the 'size' of the sound (Boubezari and Coelho, 2008). Following a similar but nevertheless distinct strategy, here we present the results of listening tests for which signal sounds have been mixed with a masking sound consisting of other sounds and random noise, with the goal of determining the detection threshold of different signals in different acoustic contexts. In all our experiments we have worked with binaural stimuli.

Sound sample preparation and listening tests

The soundscape mimicked in the listening tests was the one of the "Grote Markt", the main square of the city of Leuven in Belgium. The square is surrounded by a historical town hall, St. Pieter's church, several restaurants and apartment buildings. Due to a variety of sound sources and socio-cultural activities on this square on different days and in seasons in the year, the soundscapes occurring on this site are quite interesting. The overall most typical sounds occurring on the site are definitely human voices, human steps, bicycles, church bells and busses passing by 10 times per hour during working days. During the past years several changes were made in this square, mainly related to a reduction of its accessibility by cars for reasons of functionality, noise and safety. Nowadays, the square is considered as a pedestrian zone where only city buses are allowed to enter.

In order to make the soundscapes presented in the listening tests by headphones realistic, a hybrid combination of anechoically recorded sounds (footsteps, saxophone, talking people and restaurant sound (e.g. from cutlery impacts) convolved with the binaural room impulse response (BRIR) of the acoustic location for appropriate source and receiver positions, and in situ recorded sounds (traffic and singing birds) were prepared. A 3D computer model of Grote Markt was based on measured dimensions of the square in situ by using a laser distance meter. A simplified virtual model was constructed in Odeon9.2®. Grote Markt has an irregular shape of roughly 120 x 32 m^2 size. For the sake of making acoustical simulations, a part of the streets that terminate on this square were included in the model, resulting in a total calculation domain of about 240 x 140 m surface (Figure 1). Sound absorption and scattering coefficients of the surrounding buildings and ground surfaces were estimated based on visual inspection. In order to make the presented soundscape more realistic, the talking people were simulated by mixing sound coming from different positions on the square (respective BRIRs simulated at different source positions), while subsequent footstep sounds were simulated from a respective steadily moving source position with 70 cm step length in between).

The listening tests were realized in a silent anechoic room with background noise less than 30dB(A) in order to eliminate the possible influence of unwanted sound sources. Samples of different compositions, with footsteps (L_{Aeq}=45dB), distant saxophone music (L_{Aeq}=50dB), traffic (L_{Aeq}=54dB), talking people (L_{Aeq}=54dB) and singing birds (L_{Aeq}=45dB) as signal sounds presented at real life sound pressure level, mixed with a variable level of white noise, or pink noise (both generated in CoolEdit®), were presented by open headphones of listening unit (Head acoustics®) to 12 normal hearing people, 22 to 35 years old. The noise level was varied randomly in pre-programmed steps, such that a wide range of signal to noise ratios were achieved, from the signal sound being fully masked to the signal sound being clearly audible. For every sample, the test person was asked whether he could hear or not a particular sound.

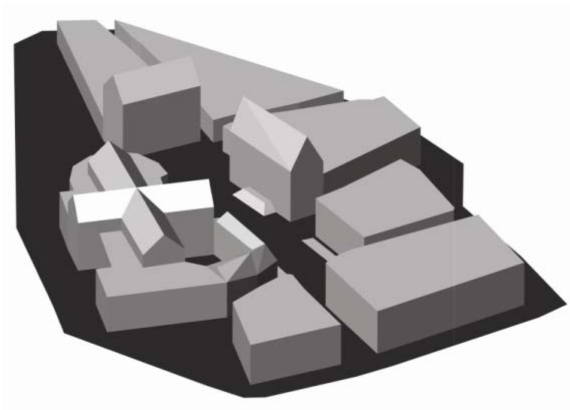

Figure 1: 3D model of Grote Markt, Leuven, Belgium

For the sake of compensating for guessing by the test persons, also some samples with signal sound absent were presented. In the next section, the results of listening test are expressed as the percentage of the times that the 12 persons on average could hear (or not hear) a sound signal of interest. All variations of noise level and type of noise, were examined for two categories of cases: in the first category, the signal of interest was mixed with (a variable level of) noise only, while in the second category, the other signals mentioned above were also mixed in together with the signal of interest and the noise.

Results and discussion

The results of the listening tests are graphically depicted for different combinations of signals and type of noise, in the presence of additional sounds (filled squares) or without additional sounds (empty squares). Example of the result presentation is given in the figure 2 and 3 that show the result for saxophone. A quick inspection of the variation within the two latter categories learns, that the spectral and temporal nature of the signal sound, as well as the type of masking sound are quite crucial for detecting its presence.

In all circumstances, the musical sound of the saxophone and singing birds abruptly change with the level of the noise. Both types of sounds are detected even in very high masking sound levels probably thanks to clear tonal components. From the five signal sounds (talking people, saxophone, birds, traffic and footsteps), the sound of saxophone has been the easiest to detect in the individual as well as in a mixed signal sound.

The detection of footsteps has been almost as easy as saxophone, most probably due to an impulsive character of the signal, e.g. sound of a short duration and high intensity. To detect a presence of talking people was slightly easier in experiments where speech was not mixed with the other environmental sounds.

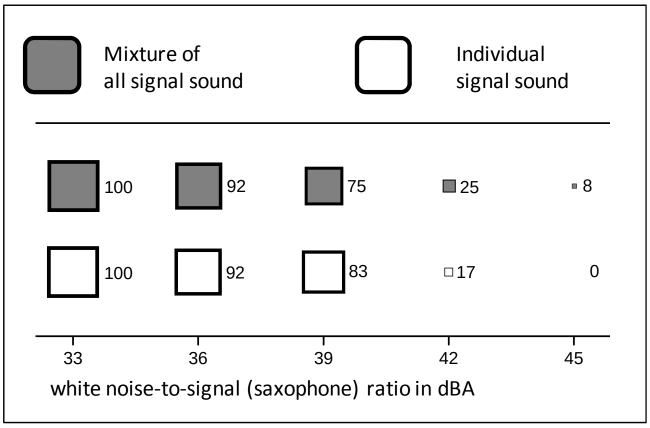

Figure 2: Example of the listening test result for saxophone as a signal sound and white noise as masking noise sound.

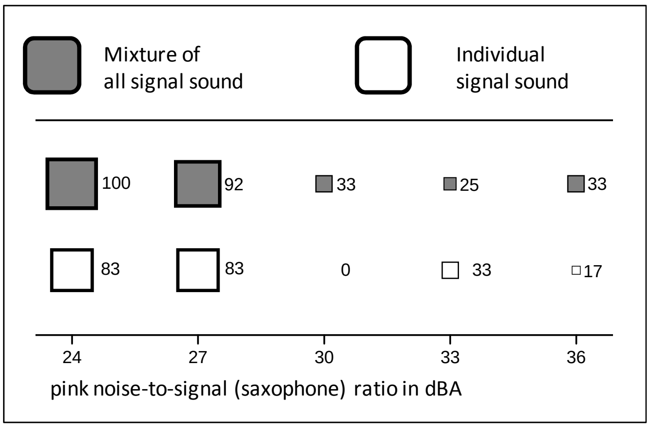

Figure 3: Example of the listening test result for saxophone as a signal sound and pink noise as masking noise sound.

Traffic noise (signal without clearly passing-by vehicles) was the most difficult to detect in both masking sounds (white and pink) as well as in both individual and mixed signal, due to its stationary character and flat spectrum, most similar to masking sounds.

Acknowledgements

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ACOUSTICAL ASSESSMENT OF URBAN PUBLIC PLACES

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1 INTRODUCTION

Design and renovation of urban public places require tight co-operation between experts from different specific fields. Only a careful design that takes into account several aspects, such as mobility, accessibility, security, density of population, biodiversity, wind, light and acoustical comfort and other, can guarantee the creation of pleasant places appreciated by city users. Urban soundscapes are often considered as a consequence of urban planning, human activity and many other non-acoustical factors, that can be influenced or tuned only within certain limits.

Acoustical assessment of soundscape in an Urban Public Place (UPP) is rather complicated, since no generally accepted standard exist so far. Soundscape assessment methods are under development by many research groups, using different objective or subjective approaches. Objective acoustical methods typically make use of acoustical measurements while considering the physics of sound propagation, and are usually performed by traditional monoaural measurements followed by statistical noise analysis. In some cases also loudness models, binaural recordings analysed by multi-parameter analysis or neural network systems are used.
Subjective methods relate to the opinion of people and usually require advanced socio- or psychological questionnaires or laboratory listening tests. In any case a strong correlation between the human judgement and objective evaluation in situ is always desired.

Each method has its advantages and disadvantages. Objective methods might suffer from the lack of information about the overall perception of sound in a location, but on the other hand, they are independent on subjectivity. Subjective methods can suffer not only from large standard deviations caused by differences in people's opinions, but also from other factors, such as subject's mood or tiredness. Human judgment is often based on the assessment of the urban situation as whole, taking all present factors into account, what makes grasping person's opinion on one specific field (e.g. soundscape) very complicated. The description of wanted acoustical situation in urban context is therefore by default very extended and should probably be defined in a different way than the one we are used to.

1.1 Existing assessment methods

Looking at already existing standardized methods, a strong preference of creators of norms is found to use a single value assessment. Standardized methods are typically focusing on objective noise quantification defined through equivalent sound level or through parameters such as the traffic noise index and estimates for the level of noise pollution[1-3]. Widely used noise regulations are also produced by the World Health Organization, OECD and different national organisations[4,5].

In parallel with the single value assessment methods a large variety of non-standardized soundscape assessment methods based on different approaches, such as, sound(scape) recognition, identification, mapping or categorisation, holistic approaches or advanced sociological methods, have been proposed[6-12].

Our study is based on the hypothesis that the human expectation in urban public place plays a dominant role in its judgement. If people get what they expect they usually feel satisfied. Larger cities can supply a variety of different urban public places so that each person can chose his/her preferred place to go for shopping, jogging, or resting. Soundscape expectation is typically interconnected with other cues such as visual, haptic etc. and with other non-acoustical factors.

This study aims at the development of a method, in which a binaural recording performed in an UPP is automatically sorted into a category, and thus indicateds if the human expectation for the acoustic nature of place can be expected to be fulfilled. The categorization is based on a set of acoustical parameters related to the sound pressure level, psychoacoustical parameters, (roughness, sharpness and fluctuation strength), and binaural information defined via the so-called urban interaural level difference.
To make the evaluation of an UPP complete a second part of the method is proposed, that consists of the semantic description of a soundscape in situ, by using 3 categories (soundmark, keynote sound and sound signals) related to features of a soundscape that cannot be grasped by the objective acoustical measurement.

2 DESCRIPTION OF THE PROPOSED METHOD

2.1 Sound recordings, analysis and clustering

A relatively large set of recordings (370) has been performed in urban public places, i.e. streets, squares and parks, where the acoustical situation has been judged by people as “normal” or “typical”. Sound samples of duration of 15-20 minutes have been binaurally recorded during so-called “soundwalks (SW)” by using in-ear microphones. All recorded data were stored into a solid-state memory of the M-Audio® recorder in binaural wave format.
The recordings were later on analyzed with respect to thirteen acoustical parameters (based on A-weighted sound pressure level $L_{p,A}$, three psychoacoustical parameters: Sharpenss *S*, Roughness *R*, Fluctuation strength *F* and one binaural parameter *uILD*). The first four parameters were calculated in time domain by 01dB Sonic®software and followed by statistical analysis in home-made Matlab® routine where each parameter was expressed by values of the parameter that has been exceeded during a fraction of x % of the recording time (L_x, R_x, S_x and F_x). A binaural parameter *uILD* has been calculated according to an algorithm described in Rychtarikova et al (2008)[13]. Finally, an optimized set of the 13 following variables has been chosen as: L_5, L_{50}, L_{95}, F_{10}, F_{50}, F_{95}, R_{10}, R_{50}, R_{95}, S_5, S_{50}, S_{95} and $uILD_2$.

Figure 1 Example of a cluster No. 7 with a photo of one of the parks clustered in it

Values of thirteen acoustical parameters were calculated for each recording, normalized and used in clustering analysis. Twenty different clusters were created by using hierarchical agglomerative clustering, available in the SPSS®software. The resulting clusters have been verified by manual identification of similarities between acoustical as well as non-acoustical properties of recordings clustered together and by identifying differences between different clusters.

Most of the sound samples were clustered consistent with objective and subjective expectations. Each cluster could be (objectively) visualized by a radar plot and (subjectively) by a verbal comment describing the common features of the places clustered together. E.g. Cluster 1 includes “streets without or with little traffic, with a speed limit of 30 km/h, typically a side street in a residential area in urban zone during day time, when most of the people are at work and side streets in the city center with a combined function, during the periods when shops are closed.” Cluster 2 contains the same places as cluster 1, with the difference that the recordings were performed during the morning and evening hours when most of the people are leaving homes or coming back from work”.

Figure 1 shows the example of cluster 7, which contains recordings performed during the daytime in city parks situated very close to main roads in an urban zone with large grass surfaces or a lake not protected from the traffic noise where the speed of cars almost never drops under 50 km/h. A detailed overview and analysis of a total of 20 clusters is given in Rychtarikova and Vermeir, 2010[14].

2.2 Semantic assessment

Automatic categorisation of a soundscape (or sound event) in a particular UPP can be successfully obtained from binaural recording in situ by the above describe method. However, to have a full impression of the evaluated soundscape, some semantic categories need to be proposed. Inspired by the book of Shaffer, three verbal categories were chosen for soundscape assessment of UPPs. (1) Soundmark, understood as a sound which is unique to an area, based on which a place can be identified (2) Keynote sound, as kind of amorphous sound that may not always be heard consciously, but that ‘outline the character’ of the people living there. This sound can be created by nature or by permanently present sound sources. (3) Sound signals, defined as foreground sounds listened consciously, such a warning devices, bells, whistles, horns, sirens, etc which can be localized.

Figure 3 Example one of the case studies in Brussels (Viaduct park), analysed by proposed semantic categories

An example of a analysed UPP ((Viaduct park in Brussel) is shown in figure 2, where a distant train sound as well as airplane sound together with typical park sounds, such as moving leaves and bird sound in the summer became a keynote sound in this park. This example belongs to cases, where sounds of nature are mixed with permanently present sound sources and are perceived as background amorphous sound. During the summer, sound signals in the park are coming from gardening machines that are used for the maintenance of the park. No Soundmarks were found in this park that would make it unique or special in comparison with other similar parks in Brussels.

3 CONCLUSIONS

This study is related to the question to what detail the differentiation between particular UPP or sound events can be successfully performed by using only objective acoustical parameters and which information/categories are necessary to be included in semantic assessment if we like to have a global soundscape description of an UPP. Twenty clusters identified in this study reflect typical acoustical situations in particular UPPs or special sound events in typical urban situation in Belgian cities. This database does not include all kinds of possible soundscapes that might exist in other countries, but new clusters can be created in future once recordings from other places would be available.
It is obvious that a single value assessment can be hardly applied when speaking about soundscape. An extension of the the single value approach to a hybrid clustering method that is based on the current acoustic measures, enriched by a semantic description, in terms of e.g. Soundmark, Sound signals and Keynote Sound in the UPP, can be expected to give a more complete and essential impression of evaluated soundscapes.

4 ACKNOWLEDGEMENTS

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Speech Transmission Index and Articulation Index in the Context of Open Plan Offices

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ABSTRACT

The evaluation of the acoustical comfort in an open plan office typically involves a rather complex acoustical analysis. Many parameters, such as the number of square meters per employee, the shape of the room, the absorptive properties of interior surfaces and background noise levels, but also the nature of the activities of the users, are determining factors.
Due to the quite complex character of this kind of a multisource environment, the way to assess the acoustical comfort differs from country to country. Often, the reverberation time is taken into consideration. However, since furniture and screens are partitioning open plan offices, the global reverberation time is not an adequate quantity to fully describe their acoustical comfort.
An alternative way to describe the acoustical comfort requirements for an open plan office is by stating the wanted minimal speech privacy together with the desired maximum value of background noise. To define speech privacy (as the opposite of speech intelligibility), two generally accepted approaches are known: the Articulation Index, and the Speech Transmission Index, or similarly the U_{50} value.
To describe the speech privacy in open plan offices a comparison is made between the Speech Transmission Index and the Articulation Index. This comparison is performed for 16 architectural setups that differ in absorption values, positioning of acoustically absorbing surfaces and the placement of furniture elements that act as acoustical screens.

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1. INTRODUCTION

In spite of the large amount of acoustical parameters that have been developed for room acoustical evaluation, the traditional reverberation time is still the most popular measure in most of the cases. However, from the acoustical point of view, the environment of an open plan office has a rather special character, which is limiting the plausibility of the reverberation time. Looking at the typical shape of these offices, one is confronted with their rather "horizontal" shape, since their width and length are much larger than their height. When furniture and screens are placed between working places, an open plan office is abruptly divided into subspaces where different reverberation times can be measured or calculated. In this way the measurement or simulation of the global reverberation time becomes a hard task.

Another problem, when trying to estimate the acoustical comfort of open plan offices in a simple way, is related to their functionality. An open plan office is a multisource environment, where several noise sources with rather different sound power, frequency spectra and time-domain characteristics can be present. Most of the sources can also be considered as receivers, as people will not only perceive sound but also produce it. Some of these sounds will be disturbing, other may enhance the speech privacy and some are not even consciously perceived. In any case, speech privacy has to be achieved, while avoiding high noise levels. As a consequence, the effective acoustical situation in an open plan office is always a compromise.

A considerable amount of research has been done by optimizing the sound absorption and the masking noise level (also called office noise) necessary to obtain a good speech privacy while keeping the sound levels acceptable. But the ultimate questions always coming from architects and users are: "How do we really aurally perceive the space?", "How do we experience the shape of the room, its sound absorption and the positioning of the absorptive materials ?", and "How is the total acoustical comfort in such a place if one is supposed to work there on a daily basis?"

One possibility to handle this issue is to simulate a number of typical acoustical simulations for every case that is going to be built, followed by an evaluation of the auralized simulated soundscape by the architect or responsible. This procedure is however very difficult to introduce in an international standard, since the subjective evaluation will always play a role in the final assessment. Therefore more objective acoustical descriptors (such as acoustical quantities that can be calculated or measured) should be considered.

In this paper, the Speech Transmission Index and Articulation index approach are compared on in the framework of a case study of an open plan office for 32 people. The main goal is to investigate, whether the different approaches lead to significantly different results and if so, in which cases these occur.

A. Speech transmission index

The Speech Transmission Index (*STI*) was developed in the beginning of the 1970's by Steeneken and Houtgast.[2] The procedure of the measurements and calculation is described in the norm CEI/IEC 60268-16. For the measurement of *STI* values, typically a loudspeaker with the directivity of a speaking person is used to emit speech-like noise, which is amplitude modulated with 14 logarithmically spaced (1/3 octave bands) modulation frequencies between 0,63Hz and 12,5Hz. These are similar to the frequencies typically found in voice signals, and therefore important for speech recognition. For the determination of the *STI* value, first, the modulation index is obtained for transmitted signals evaluated in 7 octave bands between 125 and 8000 Hz. After the longer procedure which can be found in the norm, the *STI* is calculated from the formula:

$$STI = \frac{\left(\overline{S/_N}\right)_{app} + 15}{30} \; [-] \qquad (1)$$

In which the apparent $(S/N)_{app}$ comprises not only the real signal to noise ration but also the reverberation. Values of *STI* range from 0 to1.0 , resp. from 0% to 100%.

B. Articulation Index – Privacy Index

The Articulation Index (*AI*) was described for the first time by French and Steinberg[3] as a way to express the amount of average speech information that is available to patients with various amount of hearing loss[4]. It is usually defined as a number between 0 and 1.0 or as a percentage 0% to 100%. The *AI* can be calculated by dividing the average speech signal into several bands and obtaining an importance weighting for each band. Based on the amount of information that is audible to a patient in each band and the importance of that band for speech intelligibility, the *AI* can be computed.
The Articulation Index is based on a signal-to-noise ratio assessment and is defined in the American standard ANSI S3.5 as a standardized method to assess the speech intelligibility under different conditions. The Articulation Index ranges between 0 and 1 and it is calculated from:

$$AI = \sum_{i=1}^{15} W_i \, x \, R_i \qquad (2)$$

where W_i is the weighting factor for each third octave between 200 - 5000 Hz, and R_i is the signal-to-noise ratio for each third octave band.

2. CASE STUDY

A. Model description

Our case study is an open plan office for 32 people with basic dimensions 14 x 20 m and ceiling height h = 2,7 m. The volume of the room is V = 756 m^3. Total sum of all interior surfaces depends on the amount of furniture in the room and varies between 744 and 1445 m^2.
The position of the signal source (S) and 3 receiver positions (R1, R2 and R3) are indicated in Figure 1 (right).

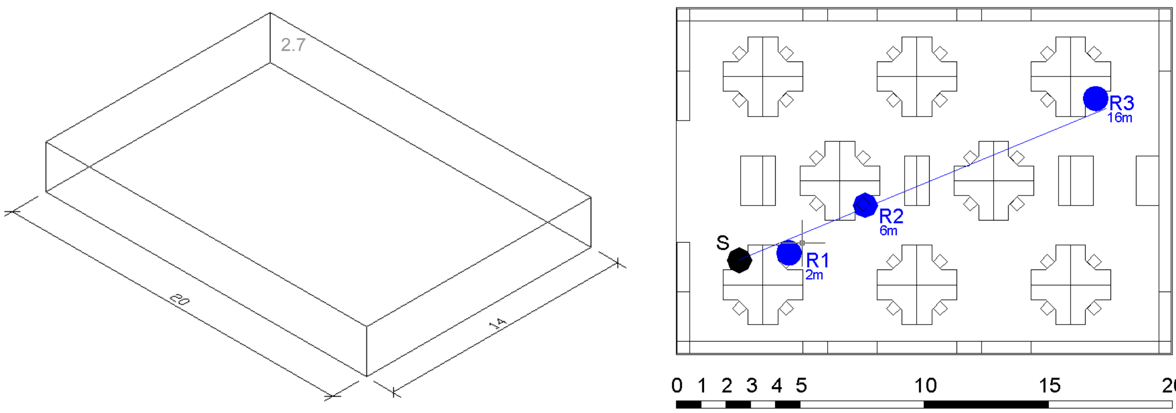

Figure 1: Basic layout of the modeled open plan office (left), table settings with indication of the signal source and three receiver positions considered in simulations (right)

Selection of the alternatives is limited to material properties of the interior surfaces that could be normally chosen by an architect. Therefore alternatives where for instance the ceiling is reflective, such as plaster, was not considered. This study is not investigating the difference between the STI and AI in general cases, but it refers to comparison of these two variables in case of the probable open plan office design. This pre-selection of materials causes that theoretically estimated reverberation time is in all cases less than 1 second and that the average absorption coefficient varies between 0.17 to 0.42 depending on alternative.

B. Description of the alternatives

In the 16 simulated alternatives the following materials were combined.

"Ceiling 1" consisted of ordinary gypsum board Ecophon Danoline M1, Ods 200 mm with ca 60% of sound absorption, standardly used in open plan offices. "Ceiling 2" was highly absorptive ceiling Ecophon Master E, Ods 200 mm with 100% of sound absorption in middle and high frequencies. The wall materials were: "Wall 1" is ordinary plaster, i.e. no absorbers, "Wall 2" is Ecophon Wall Panel C on the short wall beside the source, and "Wall 3" - Ecophon Wall Panel C on short wall + long wall besides the source. The modeled floor was made of hard wooden parquet in the case of "Floor 1", and covered with soft- thin office carpet with a thickness 4,5 mm in the case of "Floor 2".

Table 1: Summary of all calculated alternatives

case	ceiling	Free hanging elements	floor	absorptive wall panels	furniture
1	highly absorptive	no	wooden	no	no
2	highly absorptive	no	wooden	no	little
3	highly absorptive	no	wooden	no	much
4	highly absorptive	no	wooden	on 2 walls	much
5	highly absorptive	no	thin carpet	no	much
6	highly absorptive	above tables	wooden	no	much
7	highly absorptive	above tables	thin carpet	no	much
8	highly absorptive	above tables	thin carpet	on 2 walls	much
9	ordinary	no	wooden	no	no
10	ordinary	no	wooden	no	little
11	ordinary	no	wooden	no	much
12	ordinary	no	wooden	on 2 walls	much
13	ordinary	no	thin carpet	no	much
14	ordinary	above tables	wooden	no	much
15	ordinary	above tables	thin carpet	no	much
16	ordinary	above tables	thin carpet	on 2 walls	much

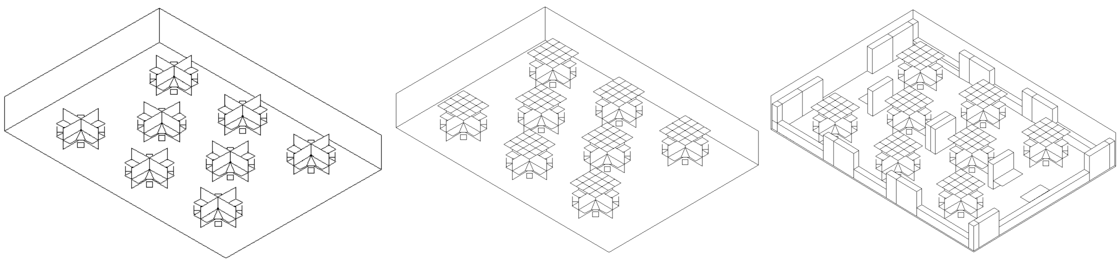

Figure 2: Examples of some alternatives. "Little furniture" (left), "little furniture + FHE (middle), "much furniture" + FHE (right)

Three alternatives were considered concerning furniture: (1) “No furniture”, i.e. empty shoebox, (2) “Little furniture”, i.e. only desks and chairs present, and (3) “Much furniture”, with desks, chairs, cupboards and trolleys. The free hanging units (FHU) that were used in some simulations were taken as Ecophon Combison DUO E, 2.4 x 2.4m, and placed on a height of 2.1m above the floor level. A summary of all simulated alternatives is given in Table 1. Some of them are shown in Figure 2.

C. Simulations

Simulations were performed in Odeon® software v.9.0, which uses a hybrid algorithm where two methods are combined to predict the impulse response of a virtual room: image source method for the early part and special ray tracing for the second part of the impulse response.
The *STI* values used for the comparison in this study are calculated directly in the software for the three receiver positions. *AI* values were calculated by using a home-made Matlab® routine from signal – to noise values/ per each octave calculated by Odeon®. Since the *AI* calculation uses third octave bands, while Odeon® reports results in octave bands, a linear approximation was used for the conversion.

The calculation of *STI* and *AI* values for each alternative was presuming the office masking noise of the 45 dB(A) with a frequency spectrum suggested by Bradley, 2003[1]. In reality the background noise in the room will be higher due to the activity of the people in the room, such as speaking, moving, breathing etc. In this study we calculate with only artificial masking noise as a background noise, because the final sound level and frequency spectrum of a crows of speaking people in the office is difficult to predict and may change due to the Lombard effect or several subjective factors.[6]

3. RESULTS AND DISCUSSION

To understand the results of *STI* and *AI* data easier, calculated sound pressure level values $L_{p,A}$ (dB) of the “Signal sound” (produced by the sound source S) as predicted at the three receiver positions R1, R2 and R3 are plotted in the figure 4 (left). Correlation between the $L_{p,A}$ values and *AI* values is obvious, however slight differences such as at the position 2 are seen, coming from the definition of the parameters itself. $L_{p,A}$ is calculated as A-weighted and summed sound pressure level, whereas *AI* is using other frequency weighting factor when used in calculation of total $L_{p,A}$.

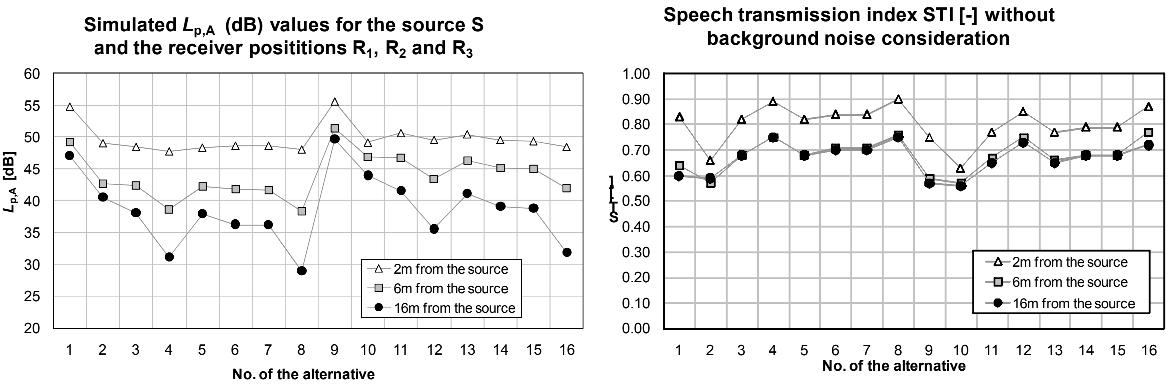

Figure 4 Simulated sound pressure level $L_{p,A}$ (dB) for the signal source S and three receiver positions R1, R2 and R3 (left) and the STI as calculated for the conditions without background noise (right)

A comparison of the 16 simulated alternatives based on predicted *STI* values is given in Figure 3 (left). The analogous comparison, taking into consideration *AI* values, is shown in Figure 3 (right). The optimum situation concerning speech intelligibility and privacy comfort is characterized by good speech intelligibility at intended listener position R1 (2m from the source) on one hand. On the other hand, weak speech intelligibility for the not targeted receiver positions R2 (6m from the source) and R3 (16m from the source) is desired, in order to create speech privacy. Both quantities (*STI* and *AI*) point out that alternatives 4, 8 and 16 result in the best speech privacy/intelligibility comfort, while the worst performance is obtained for alternatives 1, 2, and 9. Based on the result it can also be concluded that the best alternatives are those with fully furnished open plan office with an absorptive ceiling or with an ordinary ceiling + absorptive FHE, or at least two absorptive walls.

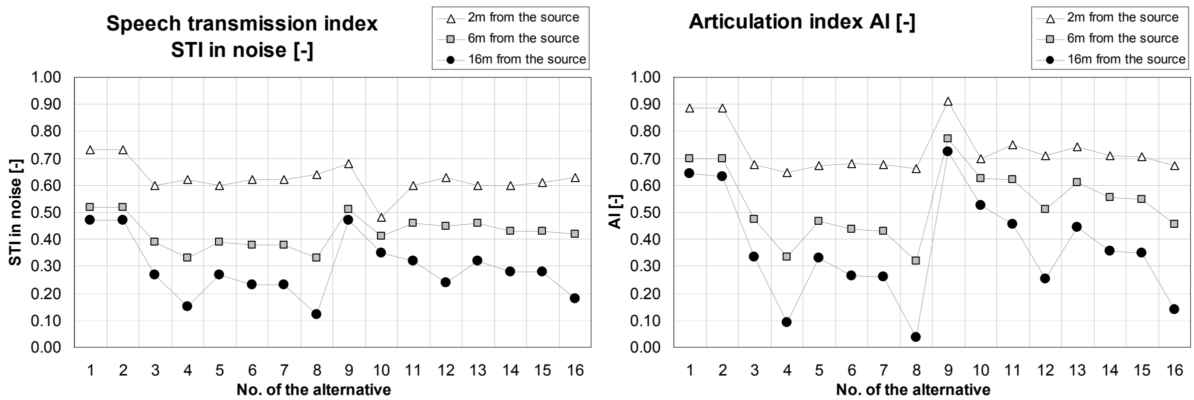

Figure 4 Sound transmission index and Articulation index calculated for 3 receiver positions in 16 alternatives

Interestingly, *AI* is predicting very high values (*AI* = 90%) for position R1 in the alternatives 1, 2 and 9, due to the fact that the reverberation is not taken into account. *AI* also predicts larger differences between different positions and alternatives than *STI*. These differences were most obvious (more than 20 %) in the alternatives 9 and 10, i.e. the alternatives with ordinary ceiling, hard surfaces and no or little furniture. A relatively large difference of about 15 % was found in the alternatives with hard floor and wall, namely alt.1, 2, 11 and 13. In the alternatives with high absorption the values of *STI* and *AI* differed less. In cases 3, 4, 5, 6, 7, 8, 12 and 16 differences were only around 5 %, and thus not significant (Figure 4).

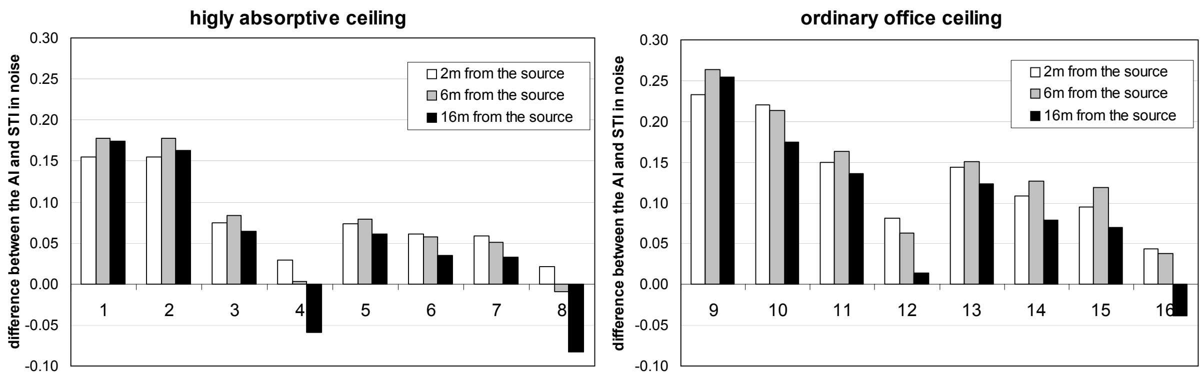

Figure 5 Differences between the Sound transmission index and Articulation index calculated for 3 receiver positions and 16 alternatives

4. CONCLUSIONS

Some differences concerning acoustical assessment of the speech privacy/intelligibility prediction in open plan offices were found between *STI* and *AI* values. Both methods have their advantages and disadvantages. Predictions of the acoustical situation by using *STI* values seem to be more realistic for general cases mainly in rooms with more reverberation and *AI*, which is only based on signal-to-noise ratios, is probably a somehow too simplified quantity when used in rooms with non-negligible reverberation. However, when speaking about the open plan office, the amount of necessary sound absorption is quite high by default, what allows usage of *AI* too.

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ROOM ACOUSTICAL SIMULATIONS FOR EXPERIMENTS ON FRONT-BACK LOCALIZATION OF SOUND SOURCES

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Abstract: Room acoustical simulations were originally developed for research in applied room acoustics and for practical purposes of acoustical consultancy that deals with prediction of the acoustical comfort in buildings or optimization of the architectural design of rooms where acoustical comfort is an important issue. Nowadays, with the emerging development of multidisciplinary research related to sound, new applications of room acoustical simulations have become a scope of interest and hearing research is not an exception. This paper deals with the question whether the Odeon software can be used for hearing research that deals with front-back localization of sound sources in rooms. In this research experiments, listening tests were performed in a real and virtual environment of an anechoic and reverberant room. Good correlation between the measurement and simulation based results indicates a good reliability of the software for the purposes of hearing research related to sound localization.

1 Introduction

As an extension to our previous experiments concerning sound source localization (in real and virtual room) in the frontal horizontal plane [1], this study is focused on accuracy of front-back localization in real and virtual room. In the experiments, non-individualized Head Related Transfer Function (HRTF) measured in the ears of the artificial head was used for Binaural Room Impulse Response (BRIR) calculations and auralisation. To access the room acoustical software for BRIR determination, comparisons were made between the situations where the BRIRs were experimentally recorded in a real room and BRIRs simulated by using a hybrid algorithm of the acoustical software ODEON®.

The main aim of this study is to investigate, whether a hybrid simulation method used for the prediction of the BRIR can be a useful tool in hearing research concerning the front-back localization of sound.

2 Measurements

Anechoic room: HRTF of the artificial head type CORTEX® MK2 in the horizontal plane was determined in an anechoic room with a precision on 15°. This procedure was done by using the VX POCKET 440 DIGIGRAM® soundcard and DIRAC 3.1® software. Measured HRTF information was translated to a plug-in format for DEON® software, which was later using them for simulations of BRIR of a reverberant room. Seven measured binaural impulse responses (Figure 1 - left) were also used directly for the creation of anechoic stimuli.

Reverberant room: Measurements of BRIRs in the reverberant room were performed by using the same artificial head and the same loudspeaker-receiver setup as in the anechoic room when preparing the HRTF information. Seven BRIRs measured in reverberant room were convolved with stimuli for listening tests. (Figure 1 – right) A reverberant room (with a volume of 198 m^3) which is typically used in room acoustics for the characterization of sound absorption of materials etc, is known by very long reverberation time, around 8s in low frequencies, ca 4,5 s in middle frequencies.

3 Simulations

All simulations of the reverberant room were performed in the room acoustical software ODEON® v.9.1, for loudspeaker-receiver positions as used in the listening setups (Figure 1). The sound absorption and diffusion properties of the surfaces in the computer model were calibrated, based on in situ measurements of the reverberation time T_{30} by using an omnidirectional loudspeaker and omnidirectional microphone.

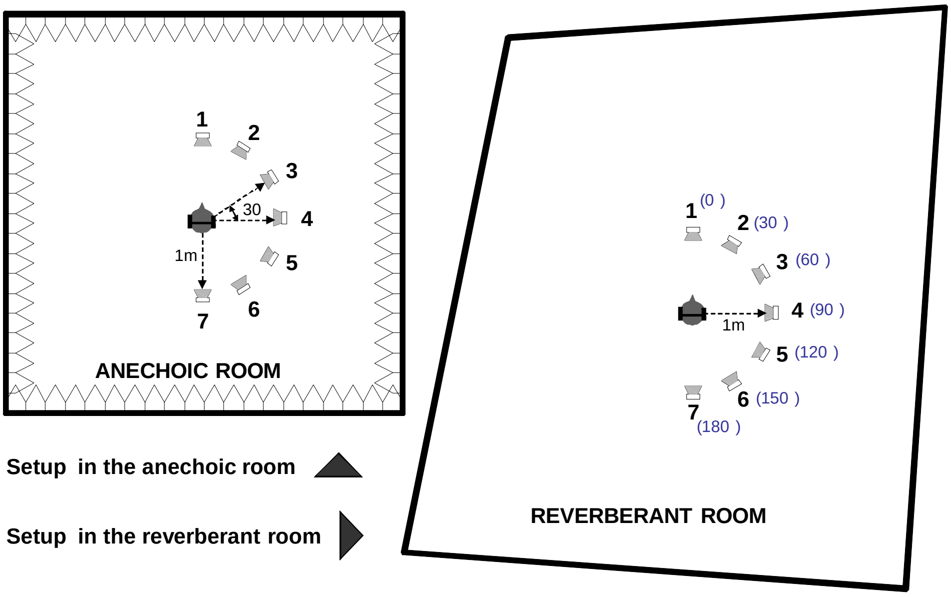

Figure 1. Setup in anechoic and reverberant room with indication of the binaural receiver and 7 loudspeakers

For the simulation of BRIR signals (later used for listening tests), the sound sources, i.e. loudspeakers type FOSTEX® 6301B were simulated with their proper frequency spectrum and directivity (as measured with precision of 10°). The receiver properties were determined by using the plug-in format of the HRTF measured in the anechoic room. Simulations of the BRIRs were performed for the standard microphones in the ear channels of the artificial head.

4 Listening tests

Listening tests were performed in two acoustical environments: an anechoic room and reverberant room. Both spaces were well insulated from the outdoor noise, with a background noise not exceeding L_{Aeq} = 30 dB. The setups used in the listening tests consisted of seven loudspeakers distributed in a half circle in the horizontal plane on the right side from the subject at a height of 1.2 m above the floor (Figure 1). Every test person was sitting on a lifted chair in the middle of the half circle so that his or her ears were at the same height as the cones of the loudspeakers. In the headphone tests, the seven loudspeakers were not active but still present in the room, in order to keep the same visual association as in tests when localizing sources naturally, i.e. by using the subjects own ears.

Eight normal hearing subjects participated in the experiments. They had a maximum hearing threshold of 15 dB HL at all octave frequencies between 125 and 8000 Hz.

The listening persons were asked to keep their head continuously pointed towards loudspeaker No. 1 (at 0°). Their task was to identify from which of the seven (real or virtual) sources labeled by numbers from 1 to 7 a sound signal was heard or appear to be heard, and to report the number to the operator. The stimuli were played in random order, with six repetitions of each sound source in every test. In this way each test resulted in 6 x 7 = 42 answers. Stimuli used in the listening tests were a broadband noise signal with the frequency spectrum of human speech and duration of 200 ms, cosine windowed with rise and fall of 50ms, presented at 65 dB (A). Every subject participated in two tests. Before each test the loudspeakers were played one by one two times and visual feedback was given to the subjects.

The accuracy in localizing sound sources in anechoic conditions were investigated under two acoustical conditions: (1) In a natural localization condition, the sound samples of signal and noise were played from loudspeakers and listened at in the free field by test persons own ears (own ears OE). (2) In a headphone based condition, where the impulse response used for synthesizing the sound had been measured in the ears of artificial head. (Artificial Head Measured AHM)

In the listening tests in the **reverberant room,** the acoustical conditions 1 (OE) and 2 (AHM) that were used in the anechoic room were repeated and one additional condition was investigated, i.e. headphone listening test, where the presented sound was based on a simulated BRIR of the reverberant room, in combination with the HRTF of the artificial head (Artificial Head Simulated AHS).

5 Results and discussion

No significant differences were found between test and retest values, so the average value from the two test were taken for later analysis. The average sound localisation performance of eight normal hearing subjects and their inter-subject standard deviation (δ) for three listening conditions are depicted in Figure 2. An Excellent localization performance for the own-ear conditions (OE) was found in both acoustical environments, with zero error for reverberant room and 0.4 error in anechoic room. Headphone listening test based on impulse responses measured in the anechoic room in the ear of the artificial head (AHM) show significantly higher error than in case of AHS (based on simulated BRIRs in the reverberant room).

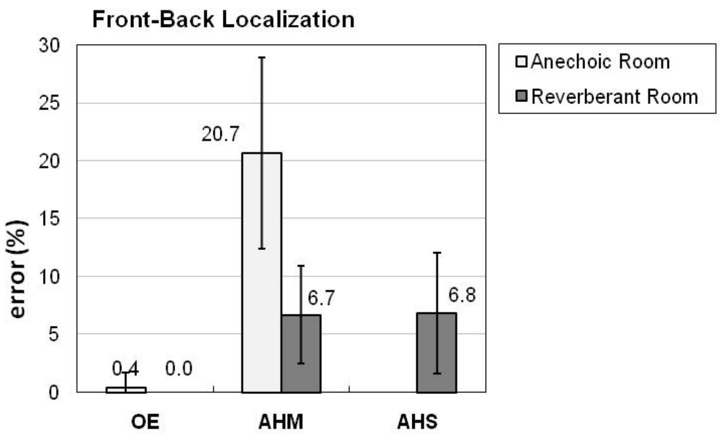

Figure 2. Average localization performance of eight normal hearing subjects and their inter-subject standard deviation for three listening conditions.

The accuracy of localisation of subjects when using their own ears (listening condition OE) is very high: the error is only 0.4% in average. With the exception of one person, everyone was able to localize sources without any mistake when only front-back errors were counted. The localisation performance dropped with 20 % on average, when sound stimuli based on non-individualized HRTFs were played via headphones under the listening condition AHM. The highest variations between the localization performance of different subjects was observed for the condition AHM (δ = 8.2). The variations were smallest in the OE tests (δ = 1.3). This observation could be expected, since the monaural localisation cues of the artificial head can be very similar to some of the subjects and very different from other subject. It is also known that some people preserve more localisation cues than others.

For the tests performed in the reverberant room, the following interesting phenomenon was observed. Under OE conditions, the localization performance was excellent, i.e. subjects were always able to distinguish between sounds coming from the front and sounds coming from the back. A comparison between the two listening scenarios under OE conditions shows that reverberation does not influence the localisation performance at all if loudspeakers are at the distance of 1m from the receiver. When testing with sounds based on a non-individualized HRTF in the reverberant environment (AHM measured in the reverberant room and AHS simulated in ODEON software) the localization performance dropped with only 6.7% (δ = 4.2) for AHM, and 6.8% (δ = 5.2) for AHS. Interestingly, when tests under AHM conditions were performed in the reverberant room, the subjects had a tendency to make less error than in the anechoic room. Further research will be necessary to explore this result.

Finally a very good correspondence was found between the tests with simulated and measured data, i.e. AHM and AHS. This indicates a good reliability of the software for the purposes of hearing research related to sound localisation.

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Soundscape Categorization on the Basis of Objective Acoustical Parameters

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Abstract

A soundscape assessment method that is suitable for the automatic categorisation of binauraly recorded sound in urban public places is presented. Soundscape categories are established as a result of an automatic clustering algorithm based on multiparameter analysis by 13 acoustical parameters used as similarity measures, on a large set of sound recordings. One of the main advantages of the followed approach allows to take into account an optimized set of parameters that are judged relevant and necessary for an appropriate description of the sampled acoustical scenarios. The Euclidian distance based clustering of the 370 recordings of typical situations based on these parameters, allows to categorize each binauraly recorded sound sample into one of 20 proposed clusters (soundscape categories). The common features among members within each cluster allow to identify "how the acoustical scenario of the members sounds like". The hybrid use of an optimized set of standard acoustical quantities, such as sound pressure level, together with well known psychoacoustical parameters that directly relate to human perception of sound, makes the propose method very robust.

Key words

soundscape, psychoacoustic, clustering, categorisation, urban public place

1. Introduction

Creators of municipal laws prefer to regulate sound in quantitative terms which are easy to measure or estimate. Assessments that can by expressed by a single value are usually desired when defining standards. For regulations concerning the building interior, the target, i.e. to achieve a sufficiently silent situation, (or other well defined situation) is clear, and it can be achieved by proper building design as a combination of sound insulation and absorption of interior surfaces. The development of guidelines for urban public places (UPPs) is a process with higher complexity. Defining universally desired properties of an ideal soundscape of an UPP is not possible. The goal of urban planners can definitely not be simplified to creating as much as possible silence. Ideally, for establishing a method and developing tools for the assessment of urban soundscapes the requirements for the acoustical situation in an UPP should be clearly described and supported by advanced sociological research reflecting the expectations of the main users of the UPP.

Urban soundscapes consist of a mixture of many different sounds with various duration, spectrum and intensity envelope, which together reveal the context. Holistic approaches for mapping soundscapes attract more and more attention. Also a large variety of non-standardized evaluation methods have been used for the description of soundscapes [1,2,3,4,5,6].

Standardized assessment methods of urban sound are typically focusing on objective noise quantification defined through equivalent sound level parameters such as ($L_{A,eq}$), L_{day}, $L_{evening}$, L_{night}, L_{den} according to EU directive on environmental noise [7], or through parameters such as the traffic noise index [8] and estimates for the level of noise pollution [9]. One widely used regulation related to noise has been produced by the World Health Organization (WHO) [10]. It contains guidelines for community noise and describe the effects of noise on health, such as noise-induced hearing impairments, sleep disturbance effects, cardiovascular and psycho-physiological effects to effects on performance, speech intelligibility and social behaviour. The WHO document also defines specific environments where noise is an important issue and gives guideline values for community noise related to the earlier mentioned critical health effects, by using two values $L_{A,eq}$ and $L_{A,max,fast}$. Other policy related documents are OECD 2008 [11] as well as many documents published on the national level of different countries. However, none of these documents focuses on a more detailed classification or typology of urban soundscapes. The particular attention to noise levels is a result of their obvious impact on human health [12,13,14], in the context of growing amounts of traffic, causing quasi permanent and continuous low frequency background noise levels in the urban environment [15,16,17].

Most researchers agree that measurements of $L_{A,eq}$ are not sufficient for the description of an overall soundscape. An overview about the urban evaluation evaluation approaches can be found in the work of [18,19,20,21,22].

The work of Adams *et al* [23] gives an overview of the information about sustainable soundscapes. It also shows how policy makers treat sound (as noise) and how individuals treat sound (with more aesthetic nuances). The authors also put forward the question how positive sounds in an urban area can be mapped and included in the evaluation of an urban soundscape [20]. A significant amount of work that relies on human-centred categorisation, such as exploring the essential features of a soundscape and the establishment of semantic criteria, were introduced by Schafer [24]. However, the main question remains open how to deal with the problem of soundscape identification, and which guidelines to propose to urban planners, in order to achieve a desirable soundscape.

Some research has been done on objective sound event recognition [25], and soundscape identification [26] but only a few authors deal with objective classification and categorisation of soundscapes in urban public places. In most of the cases only features related to spatial factors were addressed or acoustical properties of building facades were investigated [27]. Polack *et al* [28] focused on the soundscape in streets, analysing factors like road width, surrounding buildings pavement and road material, speed of the cars, and their influence on noise exposure and proposed a morpho-typological approach, dividing urban sound into four-classes based on the number of lanes in the street, and based on the question whether it concerns a one-way street or not. Their approach uses noise measurements and Multiple Correspondence Analysis, extended by cluster analysis in order to obtain the classification.

A clustering algorithm for classification of outdoor soundscapes using a “fuzzy ant” approach was proposed by Botteldoren *et al* [29]. A-weighted sound pressure level histogram, the 1/3 octave band frequency spectrum and the spectrum of temporal fluctuations were chosen as similarity measures.

The evaluation of the acoustic comfort and subjective sound level with the final goal to produce soundscape quality maps has been explored by [30] by means of an artificial neural network approach.

In this paper, we propose a classification method that is based on classifying binaural recordings made in UPPs into categories defined by a set of acoustical parameters related to the sound intensity (defined through sound pressure level), the temporal changes of the sound, evaluated through roughness and fluctuation strength, the frequency spectrum (via the sharpness parameter), and the spaciousness via the so-called urban interaural level difference [31].

The main objective of this study is to show to what extent these parameters can serve for the identification of a soundscape. Our ambition is to demonstrate to what level of detail it is possible to automatically categorize binaural sound recordings in terms of soundscape identification. In other words, we verify if and how, based on objectively measured parameters, we are able to decide how does a place sounds like.

The incentive behind this categorization approach is the hypothesis that the subjective perception of a soundscape in a given location is based on a process of comparison between the heard acoustic features, and the expected features that one is subconsciously associating with, and thus expecting for that category of location. If a “park” sounds like a “park” most people will be satisfied with the soundscape, but if a park would sound like a street with heavy traffic, people might be irritated. The negative impact of the mismatch between different components of the living environment on one hand, and the perceived soundscape quality on the other hand, have been investigated by several authors. See overview in [32,1].

2. Method

2.1 Schematic overview

The proposed classification algorithm focuses on a categorisation of sound samples that have been binauraly recorded in urban public places, i.e. streets, squares and parks, during so-called “soundwalks (SW)” that last for 15-20 minutes. The recordings were stored to an M-Audio® solid state recorder in wave format. The calibrated binaural recordings were performed by means of in-ear microphones so as to gather the sound in the ear of a city user. The sound samples were later on analyzed in the acoustical laboratory, where thirteen acoustical parameters were calculated. In a next step, the acoustical parameters were normalized and used as similarity measures in a clustering analysis that sorted locations with similar values into 20 different clusters. Finally, the clustering-based categorization was verified by identifying systematic analogies between acoustical as well as non-acoustical properties of different elements within the clusters, and by identifying systematic differences between different clusters.

2.2 Choice of the urban public places

The acoustical categories contain together 370 recordings in different UPPs in Leuven, Brussels, Namur and Bratislava, where no or few complaints of people were noted, so that these soundscapes could be considered as "normal" or "typical" for given cityscapes. One could wonder if it was not possible to combine the automatic clustering algorithm with subjective listening tests in the laboratory. Though strictly speaking this would be possible, it is not straightforward, due to the long duration (15 – 20 minutes) of the samples. Shortening the sound samples to "typical" fragments would be possible only for a few cases that have a stationary soundscape.

2.3 Acoustical descriptors as similarity measures

The acoustical parameters that were used as similarity measures for clustering, relate to (1) the sound intensity defined through the sound pressure level A-weighted ($L_{\mathrm{p,A}}$), (2) temporal changes of the sound evaluated through Roughness R and Fluctuation strength F, (3) some information about the frequency spectrum given through the centre of gravity of the frequency spectrum defined as Sharpness S and (4) the spatial sound impression described through the so-called urban Interaural level difference $uILD_2$ [31].

The statistics of the evolution of each parameter over a sound sample (L_x, R_x, S_x and F_x) is expressed by the values of the parameter that has been exceeded during a fraction of x % of the recording time, with the fraction typically taking the values 5% (exceptional events), 50% (probable situation) and 95% (quasi continuous situation).

The calculation of the values of four acoustical parameters ($L_{\mathrm{p,A}}$, R, F and S) in time domain was performed in the 01dB Sonic® software and the determination of their statistical values as well as the calculation of $uILD_2$ was performed by a home-made Matlab® routine.

Sound Pressure Level *L* [dB]

The sound pressure level *L* has been chosen as one of the similarity measures due to its simplicity and general use in acoustics. "A-weighted" spectra of recorded sound fragments for the calculation of the instantaneous sound level were chosen, and a "fast" time constant of 125 ms was selected for sound level. Statistical noise levels were calculated in the standard way, described in the previous paragraph.

Roughness *R* [cAsper] **and Fluctuation strength** *F* [cVacil]

Temporal variations of sound result in two kinds of impressions: the fluctuation strength, which expresses slow variations of the loudness (< 20 Hz), and the roughness. The sensation of fluctuations reaches a maximum level of perception at 4 Hz and then decreases towards higher and lower frequencies. Above 10 Hz, a new sensation appears. The loudness is perceived to be constant and an increasing feeling of roughness appears, reaching a maximum around 70 Hz. The unit of fluctuation strength can be understood as follows: a 1 kHz signal of average level L_p=60 dB that is amplitude modulated by a sinusoidal modulation function of frequency $f_{modulated}$ = 4 Hz with a modulation depth of 100% yields a fluctuation strength of F = 1 Vacil [33].

To calculate roughness, more methods are known. In our research the method developed by Zwiker and Aurés, is used which calculates a specific roughness by critical band and the global roughness being the sum of all specific roughnesses. The calculation of roughness is based on the determination of the relative fluctuations of the envelope of excitation levels of 24 critical bands. A 1 kHz signal of average level L_p=60 dB that is modulated by a sinusoidal modulation function of frequency $f_{modulated}$ = 70 Hz with a modulation depth of 100% yields a roughness of R = 1 Asper [33].

The calculation of all psychoacoustic parameters was based on a time series of Loudness values, which were determined from the sound recordings in time intervals of 2 ms. Roughness values were calculated over intervals of 500 ms from the Loudness time series. For the fluctuation strength the sequence length was 1000 ms.

Sharpness

The sharpness *S* [acum] of a sound sample is related to the centre of gravity of the envelope of its amplitude spectrum. Neither the detailed spectral structure, nor the overall level, have significant influence on calculated sharpness values; sharpness increases only with a factor of two for a level increment from L_p=30 dB to L_p=90dB. When few one of more tones fall within one octave band, they cannot be distinguished by the sharpness parameter. The unit of sharpness, 1 acum, is achieved for narrow-band noise of one critical octave bandwidth at a centre frequency of 1 kHz and of a sound pressure level of L_p=60 dB [33].

Binaural parameter

The importance of the binaural aspects of hearing on the perception of acoustical comfort in the urban environment has been mentioned only in few studies and a related quantifier has been rarely used for describing urban soundscape. For our research, the parameter called "urban interaural level difference" ($uILD_2$) was developed [31]. $uILD_2$ reflects the level difference between the left and right and is defined as:

$$uILD_2 = \sum_{i=1}^{n} \sqrt{\frac{(L_{Li}-L_{Ri})^2}{n}} \qquad (1)$$

where L_{Li} and L_{Ri} are respectively the value of sound pressure level in the left and right ear channel at time i, and n is the number of values. $uILD_2$ expresses the directivity of the received sound, and thus reflects to what extent sound sources sound localized. $uILD_2$ increases as the direct to reverberant sound level difference increases.

2.4 Clustering method

The categorization of UPPs by multi-parameter analysis was done by hierarchical agglomerative clustering, a method that is available e.g. in SPSS® software. Hierarchical clustering analysis is based on the calculation of Euclidian distances between the samples, which is then followed by an agglomerative or divisive method to categorize them. In the agglomerative method used here, first each object is treated as a separate cluster. Then, grouping is done into bigger and bigger clusters [34].

Previous research [31] has demonstrated the use of statistical values based on L, N, R, S, F for categorizing a set of 90 soundwalks. Clustering by using only L_{95}, N_5, F_5, R_5, and S_{50} was not very successful. Later on [35] an extended set of 27 parameters, also based on binaural parameters, was used with satisfactory results.

However, strong correlations were found between some parameters (such as between R_{95} and $R_{90,}$ and between S_5 and S_{10}) and therefore here a reduced and optimized set of the 13 following parameters is used: L_5, L_{50}, L_{95}, F_{10}, F_{50}, F_{95}, R_{10}, R_{50}, $R_{95,}$ S_5, S_{50}, S_{95} and $uILD_2$.

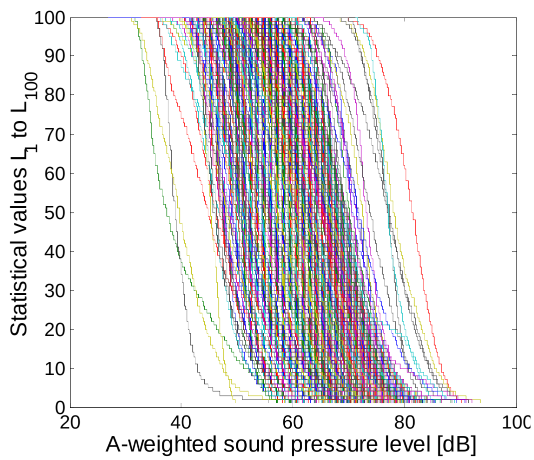
3. Results and Analysis

The 13 parameters defined above were calculated for 370 “soundwalks” (Figure 1 to 3).

Figure 1 (left) shows that the spread of the data used for the analysis ranges between the most silent samples, with L_{95} less than 35 dB and L_5=45 dB, up to noisy samples that have L_{95} higher than 75 dB, and L_5 almost 90 dB. The curves have also different slopes. This expresses differences in the temporal structure, and thus also differences in the peak to basic sound level contrast quantity L_5 - L_{95}.

The spread of Sharpness values (Figure 1- right) follows an almost normal distribution, except for a few samples with S_{50} varying between 1 and 2 cAcum.

Figure 2 shows that the Roughness and Fluctuation Strength have a relatively broad spread in overall values, in slopes, and mainly in peak values. The statistical distribution of $uILD_2$ over the whole set of soundwalks is depicted in Figure 3. Most of the values range between 2-3 dB.



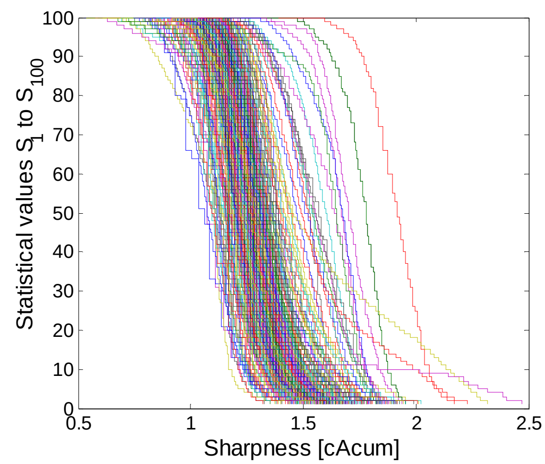


Figure 1 : Distribution of the statistical values of sound pressure level (left) and sharpness (right) calculated from 370 soundwalks

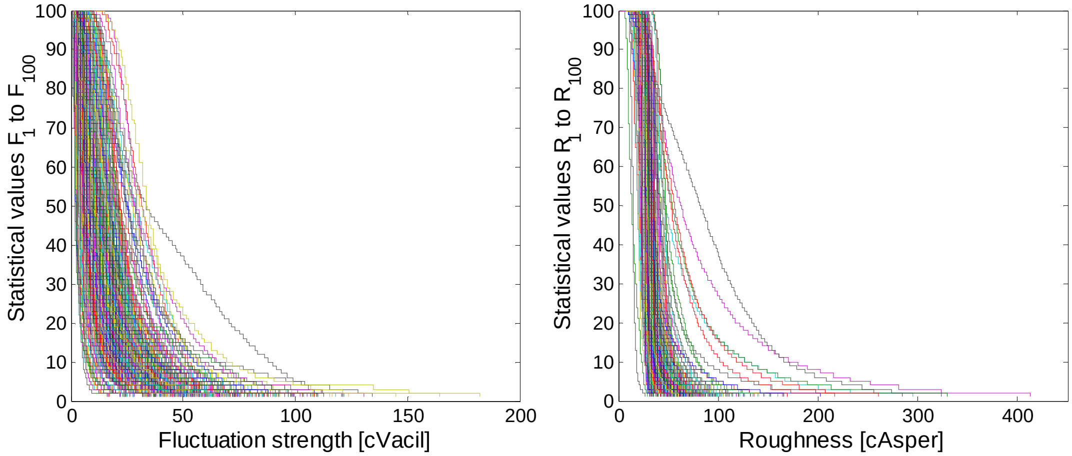


Figure 2 : Distribution of the statistical values of roughness (left) data fluctuation strength (right) calculated from 370 soundwalks

Since each of the similarity measures is defined in different units and with a typically different range of values, normalisation of the data is necessary. Two ways of normalization were tried. A linear normalization (rescaling of the data in a given interval [min,max] to the standard interval [0,100]) of the values was tested [35] but several inconveniences were observed, e.g. just a few extreme sound situations with very extreme value of e.g. R_{10} caused a loss of differentiation between samples on basis of the R_{10} and a less adequate classification. Normalization on the basis of the mean <M> and the standard deviation σ_M of the population (370 cases) of every similarity measure M, i.e. rescaling every value M to (M - <M>) / σ_M, led to much better results and was used in this paper.

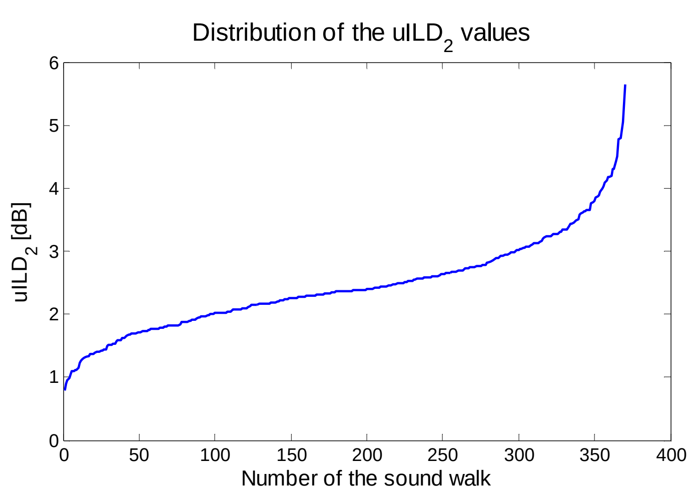


Figure 3 : Distribution of $uILD_2$ values

Analysis of the found clusters

The main objective of the following analysis is to find out whether the recorded UPPs were clustered in a logical way, i.e. consistent with the overall "spatial features" (such as architectural characteristics in the urban place) of the members of the cluster, and with their "temporal features" (such as auditory event structure).

The automatic clustering algorithm has produced clusters with different number of elements in each of the cluster. Seven out of twenty identified clusters contain more than 10 elements and one of the clusters is significantly larger in comparison with the rest, containing more than 100 elements. This result is a logical consequence of the dominance of recordings of main streets in cities in the examined set of UPPs, and the presence of a number of acoustical recordings that were taken in a particular acoustical scenario (such as during a football match or a cycling competition in a city). Those circumstances were recorded less often and so the clusters containing these recordings are relatively smaller.

In the following, we address the important question whether the separation between all clusters and the similarity between the properties of different members within each cluster is consistent with global expectations by humans. If yes, the proposed method effectively can be used to categorize urban soundscapes, and the categories can be used for descriptive or normative purposes.

Cluster 1 contains 61 sound samples from which 17 are side streets in residential areas in urban zone recorded during the evening, 18 are side streets in the city center with a combined function, i.e. they connect dwelling houses and shops, recorded during the periods when shops are closed (evenings and Sundays), both without or with little traffic, with a speed limit of 30 km/h. Eight sound samples had been recorded on squares in the city centre accessible by cars, typically at the end of a dead end street or with very limited traffic. Some of the squares are used as parking places. The remaining eighteen sound samples in cluster 1 were recorded during day time in parks along not too busy bicycle pads.

Cluster 1 can be in general understood as a category for urban soundscape where different urban sounds are balanced, without a typical sound being dominant. In these places cars are passing by from time to time at low speed. People were walking through the area rather rarely and sometimes a few natural sounds like birds were also present. The mean L_5 in this cluster was measured 60 dB, L_{50} = 50 dB, and L_{95} = 45dB. Radar plots of the clusters are shown in Figure 4. To illustrate the shapes of the clusters better, the data plotted in all radar plots have been linearly rescaled to the range 0 and 100. The dotted lines in the radar plots indicate the minimal and maximal values of each parameter in the cluster.

At first sight, Cluster 2 looks similar to cluster 1, but if we have a look at the data in more detail, the difference is clear. In cluster 2, higher values of sound levels and roughness can be observed, due to increased traffic. Most of the samples clustered here were obtained for the same streets in residential areas as in the cluster 1, but now during the day time, rather than in the evening (respective recordings in cluster 1). Cluster 2 has 23 elements from which 11 are the streets mentioned, 5 samples are from parks in the city centre situated next to a traffic sign indicating a 30 km/h speed limit and recorded during day time. Six squares of a smaller size with some public functionality (such as a pub or shop present) and a speed limit also 30 km/h where categorized in this cluster too. One sample in this cluster was recorded on a main road. This can be explained by the fact that the recording was done during a 15 minutes period during which the intensity of the traffic situation was coincidentally exceptionally low.

The sound intensity parameters in this cluster were L_5 = 66dB, L_{50}= 56 dB and L_{95}= 50 dB. On average, these values are about 5 dB higher than in cluster 1.

Cluster 3 contains the largest amount of elements (110). It is worth to mention that most of the recordings in this study were performed in main streets of 4 cities. 69 of those, recorded in evening time in the city center, with speed of the cars between 30-50 km/h, appeared in cluster 3. Fourteen side streets with speed limit 50 km/h, recorded during the day, were clustered here as well. Other cases categorized in cluster 3 are five parks situated close to the main road in the city center, separated from the roads only by trees (thus no wall or buildings), and 22 squares in urban zone, where traffic is passing through the square. On average L_5 = 72 dB in this cluster, L_{50}= 62 dB and L_{95}= 53 dB.

Cluster 4 contains 53 main streets in the city centre and urban zone during peak hours at day time, with a dominant sound of vehicles moving at a speed of 50 km/h. On average L_5=78 dB, L_{50}= 69 dB and L_{95}= 60 dB in this cluster.

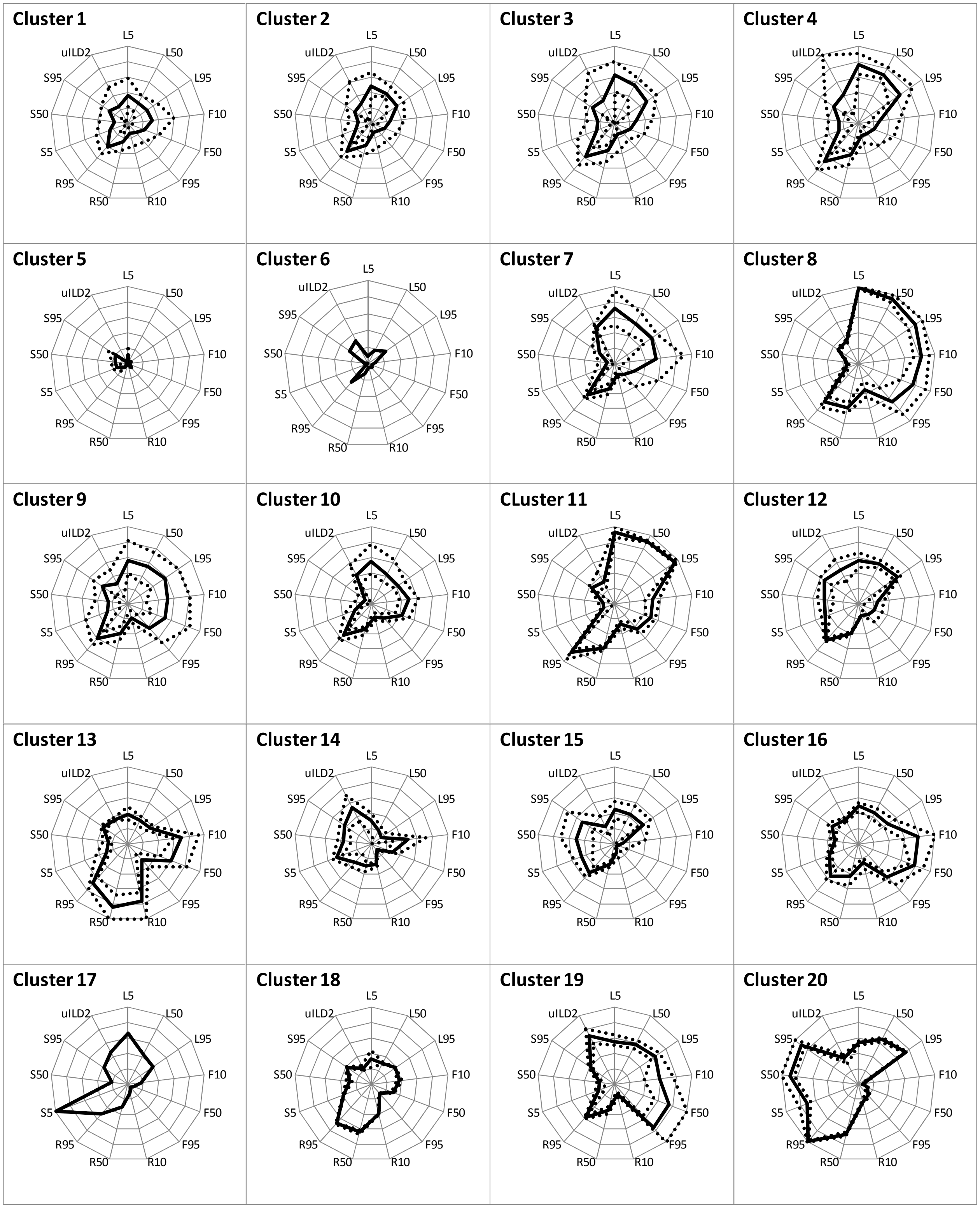


Figure 4 : Overview of the clusters categorising the soundscape in urban public places

Clusters 1-4 have typically low values of fluctuation strength, typical for soundscape a without dominant sound of human voices. On average, the sharpness values in these clusters are low, due to more neutral spectrum of sound or more low frequency components in the sound in these clusters. The radar plots of these 4 clusters have a similar shape, increasing from 1-4 mainly in two directions, e.g. vs higher sound pressure levels and vs a higher roughness of sound.

Cluster 5 and 6 were found to be very quite and silent clusters. Cluster 5 contains recordings performed in an urban residential area during night hours, between 1-3 a.m. with the average L_5 = 50 dB, L_{50}= 38 dB and L_{95}= 34 dB. It can be seen that all parameters have very low values (Figure 4).

Cluster 6 contains measurements in a quiet place in the middle of the large park during the day without wind. L_5 = 49 dB, L_{50}= 45 dB and L_{95}= 43 dB.

The sharpness measures S_5 and S_{50} during the night in residential areas are slightly higher in comparison with the measurement done in a silent park place during the day. The sound levels L_5 were the same in both situations, though L_{50} and L_{95} were higher in the park. This is logical since the basic background noise level in cities is higher during the day than during the night hours.

Cluster 7 contains seven recordings from parks close to main roads in an urban zone where the speed of cars almost never drops under 50 km/h. These parks were open, with large grass surfaces or a big lake, and not protected from traffic noise (not even by trees). Measurements were done during day time and on average L_5 = 76 dB, L_{50}= 63 dB and L_{95}= 57 dB. These values are very similar to the ones in cluster 4. The difference between clusters 4 and 7 lies mainly in the fluctuation strength and in a very stable $uILD_2$ value in cluster 7. High and stable values of $uILD_2$ indicate an acoustic scenario where a good identification of dominating sound sources is possible, in this case the noise of cars on the nearby main road on one side of the park. Due to the open character of the situation in the absence of surrounding buildings, reflections of sound waves are absent, so that the noise of the cars is clearly coming from one direction. The $uILD_2$ value along a main road surrounded by buildings is obviously lower, since the reflections of buildings result in spreading of sound to all directions.

Cluster 10 can be described as collection of streets and bicycle pads in the campus, with few students passing by walking or cycling, and of residential areas with family houses and large

gardens in front of the house during the time when people leave their homes to go to work and or return home from work. In this cluster L_5= 68 dB, L_{50}= 56 dB and L_{95}= 50 dB on average.
The sound pressure level values are similar to cluster 2, however, a higher fluctuation strength was found in cluster 10, due to the presence of more bicycles and talking people passing by.
Cluster 13 contains 4 sound samples recorded in a park during maintenance activities, such as the cutting of trees. This cluster is thus related more to a particular sound event, rather than to a location as such. Obviously, due to the rough, low frequency noise of the cutting machines, very high values of roughness and fluctuation strength F_{50} and F_{10} and very low values of sharpness were observed. $uILD_2$ and sound level values are also not very high, since the maintenance was recorded from a distance of few 20 - 30 m. On average L_5 = 62 dB, L_{50}= 52 dB and L_{95}= 47 dB.
All recordings in Cluster 14 were taken in relatively quiet places where one of the dominant sounds were footsteps of people passing by. Recordings originate from quite parks or residential areas with family houses and the average L_5 is 58 dB, L_{50} = 46 dB and L_{95}= 38 dB.

If the clustering algorithm was based only on statistical noise levels, the recordings from the cluster 15 and 16 would be probably clustered together in the cluster 2. However, their qualitative properties are rather different and this is a nice example of how the proposed method can handle these qualitative differences.
Cluster 15 can be defined as category of residential areas in relatively quiet streets with lots of trees or parks during windy summer days. Sharpness and roughness values reach from moderate to high values, whereas the fluctuation strength is minimal. Average values were L_5 = 64 dB, L_{50} = 56 dB and L_{95} = 51 dB. This cluster illustrates the influence of the weather and season on the recordings and on the soundscape categorisation.

Cluster 16 contains four recordings performed by a person walking through narrow streets (6-10 m width) not accessible for cars, with lots of restaurant terraces during warm summer evening nights. Human voices form the dominant sound, which is confirmed by high fluctuation strength values. $uILD_2$ is rather low, due to the terraces being on both sides of the street so that the “soundwalking” person was continuously surrounded by sitting and talking people. Average L_5 = 66 dB, L_{50} = 57 dB and L_{95} = 52 dB.

Cluster 9 contains 49 samples recorded in UPPs with many people present: 27 traffic free shopping streets during opening hours of shops with talking people passing by, and 22 squares during warm summer evenings and nights with people sitting in outdoor restaurants or crossing the square. Mean values of L_5 = 69 dB, L_{50}= 62 dB and L_{95}= 57 dB.

In cluster 19 two streets and two squares were found that are characterized by people passing by at shorter distance from the “soundwalking” person. In this cluster L_5 = 69 dB, L_{50} = 63 dB and L_{95} = 58 dB. This cluster differs from cluster 9 mainly concerning the value of $uILD_2$ and the fluctuation strength, which are much higher in cluster 19 due to the wider character of the site, which helps to make differences in sound intensity between the left and right ear larger than in situations where the reflections from the surrounding building are more significant. It is also possible that the reflections from the buildings can help in smoothing the fluctuation strength when comparing cluster 9 to cluster 19.

Samples clustered in cluster 12 strongly relate to sound events in the squares and streets, particularly to cleaning of the UPP by a dedicated vehicle. The mean values of L_5 = 69 dB, L_{50} = 63 dB and L_{95} = 58 dB.

Cluster 18 collects sound samples recorded while walking in the park that is moderately quite, with hearable footsteps of the “soundwalking” person. Without the footstep sound, these soundwalks would probably be associated with cluster 2. Cluster 18 differs from cluster 14 (where the footsteps were a dominant sound) not only in the sound level but also in $uILD_2$ value, since the sound of the footsteps from the “soundwalking” person itself is equal in both ears (cluster 18), whereas sound of the footsteps of people passing by creates larger differences in sound intensity in the left and right ear (cluster 14). Average L_5 = 66 dB, L_{50} = 57 dB and L_{95} = 52 dB.

Cluster 17: One recording in our research was done at a restaurant terrace which is situated in the square very close to a railway road. The sound of a train passing by changes the local soundscape so much that this sample appeared in a separate cluster (cluster 17), with L_5 = 73 dB, L_{50} = 57 dB and L_{95} = 49 dB.

Cluster 20: Some acousticians often recommend designing a fountain in the park or a square, where the noise of the cars can be a disturbing issue. Three parks with a fountain have been recorded in our study and all of them have been grouped correctly together in cluster 20, which is characterized by very high values of sharpness and roughness R_{95}. The average sound level in these situations reached values L_5 = 68 dB, L_{50} = 67 dB and L_{95} = 63 dB.

Cluster 8 and cluster 11 express sport events. Recordings performed during the cycling competition were associated with the cluster 8 which soundscape can be described as people speaking, shouting and applauding, mixed with car and helicopter sound. The mean values are L_5 = 87 dB, L_{50} = 79 dB and L_{95} = 70 dB.

Cluster 11 contains 4 recordings during soccer games with similar mean values of sound pressure level (L_5 = 85 dB, L_{50} = 77 dB and L_{95} = 72 dB), as in Cluster 8 related to cycling competition, but different fluctuation strength and roughness values. $uILD_2$ in both cases is very small due to relatively large envelopment by sound of talking shouting people when sitting/standing in the crowd.

4. Conclusions

A novel approach to acoustical categorization of urban public places, based on objective analysis of binaural sound recordings *in situ* has been outlined. The objective clustering is found to be consistent with subjective expectations on the basis of the typology of the recording locations and activities.

The definition of clusters by multiparameter analysis performed on *in situ* recordings is thus useful for categorization of the recording in terms of expressing “how an acoustic scenario sounds like”.

The 20 clusters identified in this study reflect typical acoustical situations in particular UPPs as well as special sound events. New clusters will be added in future, as new records will be added to the database.

Most of the 370 sound samples were clustered according to selection rules that can be useful and detailed enough for urban public place evaluation from the acoustical point of view.

It has been demonstrated to what detail the differentiation between particular UPP or sound events can be successfully performed by using only objective acoustical parameters. Extension of the current approach to a hybrid clustering method that is based on the current acoustic measures, enriched by a semantic description, in terms of e.g. Soundmark, Sound signals and Keynote Sound in the UPP, can be expected to give a full and comprehensive impression of the evaluated soundscapes.

A strong advantage of the proposed method is the use of the well known and generally used objective acoustical parameters for physical quantification of noise, i.e. sound pressure level, together with known psychoacoustical quantities that directly relate to human perception of sound and that have been thoroughly tested in acoustical laboratories.

In this way, locations measured by our approach can be still evaluated by data from classical approaches that deal with statistical noise levels only if necessary (since Lp is one of our similarity measures). In this case, further discrimination on the basis of clusters can be used for more detailed specification of the soundscape in a given place.

Given this objective classification of soundscapes into clusters or categories, the next research step will be to seek for correlations between the cluster structure on one hand, and *a priori* subjective categorization by people experiencing the respective urban public places on the other hand. If such a correlation could be established, this would open the way to design or adapt urban public places to match people's expectations solely on the basis of objective numbers and without the need of consulting.

While preparing a method for assessment of the urban soundscape, experts from other field (such as mobility, density, wind comfort, biodiversity and universal design) should be involved as well, and a guideline for urban public place must be understood as a compromise between different scientific fields.

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Figure captions

Figure 1 : Distribution of the statistical values of sound pressure level (left) and sharpness (right) calculated from 370 soundwalks

Figure 2 : Distribution of the statistical values of roughness (left) data fluctuation strength (right) calculated from 370 soundwalks

Figure 3 : Distribution of $uILD_2$ values

Figure 4 : Overview of the clusters categorising the soundscape in urban public places

Luisteren naar de geluidomgeving

Gerrit Vermeir, Monika Rychtarikova

Het woord *sprekend* wordt dikwijls in zijn overdrachtelijke betekenis gebruikt. Wij hebben het over sprekende gelijkenissen, sprekende getuigenissen, maar blijkbaar ook over sprekende lokalen?[i] Het sprekende lokaal is dan de suggestieve metafoor voor een lokaal of een gebouw als levend organisme. Met de uitdrukking ‘sprekende ruimten´ wil men vooral het bewuste luisteren stimuleren. Het luisteren betreft dan de auditieve perceptie van geluidgolven die ontstaan zijn binnen de ruimte en die door interactie met de omgeving speciale kleur en betekenis krijgen. Een voetstap, een stemsignaal, een vallend voorwerp, het bespelen van een instrument... iets moet alvast de golfbeweging in het luchtmedium veroorzaken. De zich voortplantende golfbeweging interageert vervolgens met de begrenzingen van de ruimte. De weerkaatsing en verstrooiing op de wanden en objecten zorgt voor bijkomende geluidgolven die zich bij de directe golf voegen. Deze golven komen ook wat later aan bij de toehoorder dan de directe golf. Zij hebben een andere klankkleur, een andere sterkte, een andere richting. Daardoor wordt in het gecombineerde klanksignaal heel wat informatie opgeslagen, waardoor onze auditieve perceptie van afstand tot de bron , van omvang en richting van de bron, van afstand tot de wanden en van de aard van de omgeving wordt ondersteund. Een waarnemer met een visuele beperking gaat extra attent van deze informatie gebruik maken. In een gesloten ruimte worden deze reflecties in de loop van de tijd ook steeds talrijker en gaan mekaar versterken.

Afhankelijk van de binnenafwerking gaat bij de weerkaatsing ook in meer of mindere mate golfenergie verloren. Het geheel resulteert in het nagalmfenomeen. Als galm lang doorgaat kan deze hinderlijk worden: de spraakverstaanbaarheid wordt dan moeilijker en de reflecties verhogen het geluidniveau in de ruimte. Een al te galmende stationshal is hier een bekend voorbeeld van, maar ook tal van kathedralen en kerken hebben dikwijls een galmende akoestiek. We zijn zeker ook bekend met het fenomeen van een ruimte waar heel veel mensen samen proberen te converseren. Het vele geluid in de ruimte verplicht ons individueel tot luider spreken om ons verstaanbaar te maken. Zo neemt de steminspanning voor iedere aanwezige spreker toe. Zeker wanneer de ruimte akoestisch hard afgewerkt is (veel steenachtige tegels, glad bepleisterde wanden), is dit laatste een zeer hinderlijk fenomeen. Men noemt dit het cocktailpartyeffect. Ook voor muzikale toepassingen is overdadige galm ongewenst: de muziekuitvoering verliest dan gewenste duidelijkheid, helderheid, definitie. Met dit onderwerp zijn musici en zaalakoestici erg begaan. Maar reflecties en de nagalm die ermee samenhangt, heeft dikwijls ook zeer positieve effecten. Dankzij de reflecties draagt het geluid immers tot dieper in de ruimte en dankzij de reflecties wordt de klank ondersteund en krijgt hij de gewenste klankkleur.

Het boek van de auteurs Blesser en Salzer[i] brengt dit zaalakoestisch thema over naar de bredere auditieve ervaring van de architectuur en van de gebouwde omgeving. De titel zou immers evengoed kunnen zijn: over akoestiek en architectuur.

Pragmatisch bekeken is deze relatie vrij evident: de akoestische problemen die zich stellen bij het realiseren van onze bebouwde omgeving vormen voor hen die zich op bouwakoestiek toeleggen, ofwel een inspiratiebron wanneer het om onderzoeksmensen gaat, ofwel een bestaansreden voor hen die zich toeleggen op het adviserende werk of op de technische uitvoering ervan.

In het historische perspectief wordt de band tussen architectuur en akoestiek veelal gelegd via de muziek. In de boeken van Vitruvius 'De Architectura' vindt men daar een mooie illustratie van. Deze 10 boeken vormen een handleiding voor de Romeinse architect. In boek vijf vindt men naast voorschriften voor forum en basilica, schatkamer en gevangenis, voorschriften voor plan en akoestiek van theaters, beschouwingen over muzikale harmonie, en daarop gebaseerd, gedetailleerde voorschriften voor bronzen vazen die in speciale nissen in de publiekzone voorzien werden. De reeks vazen dient een klank te produceren

afgestemd op één, of voor grotere theaters, op drie toonladders. Volgens de geschriften is het doel het verhogen van de klaarheid van het geluid en het opwekken van harmonieuze klanken in unisono met de op het podium geproduceerde klank. De relatie met de muziek en met de daarmee gepaard gaande leer van de harmonische proporties is doorheen de geschiedenis als metafysische band steeds in de belangstelling geweest. Voorschriften in verband met de aanbevolen proporties van een muziekzaal vindt men regelmatig terug in de geschriften. Zo werd vroeger gedoceerd dat de ideale verhouding breedte/hoogte/lengte van een zaal zou dienen te beantwoorden aan de gulden snede. Men kan vlot aanbevelingen terugvinden die inspelen op superieure verhoudingen gelijk aan 2/3/5, dus volgens een Fibonacci-reeks waarvan de verhouding van de opeenvolgende termen streeft naar 1,618…(de gulden snede). Of dit als voorstel zinvol is, wordt bijvoorbeeld door een prestigieuze zaal als de Weense Großer Musikvereinssaal niet bevestigd, en zeker niet door de trends in hedendaagse ontwerpen. Het zaalakoestisch onderzoek heeft overigens uitgewezen dat hier een zeer behoorlijke rek op zit.
De specifieke bijdrage van de akoestiek van een ruimte tot de ruimte-ervaring als zintuiglijk gegeven, heeft in eerste instantie betrekking op het toevoegen van de dimensie tijd als een soort zesde zintuig. Het antwoord van de ruimte op een signaal, zoals voetstappen, vertelt veel over de aard van een ruimte. Wetenschappelijk gezien is het trouwens de impulsresponsie die als tijdsfunctie de fenomenen ten volle kan beschrijven. Om een gebouw te ervaren moet men het gehoord hebben en in tegenstelling tot de visuele waarneming, is onze woordenschat dienaangaande vrij beperkt. Over geluidervaringen kunnen wij blijkbaar moeilijk communiceren. Zeker in onze westerse culturen is het beschrijven en documenteren van visuele impressies ingeburgerd, alleen in de kunst komt subjectieve en individuele benadering van het visuele beeld nog op de voorgrond. Een visueel beeld is ook omzeggens statisch: het is er nu, en daarna ook nog. Het auditieve beeld is dynamisch: de informatie-inhoud en de subjectieve interpretatie komen hier immers voor een groot deel uit het tijdsverloop van de signalen. Er zijn geen codes om het over een geluid te hebben, wij beschrijven alles vanuit de situatie. Leg maar eens niet professioneel uit waarom een muziekuitvoering heeft aangegrepen, waarom een geluidomgeving inspirerend was... Maar dit hoeft geen nadeel te zijn, het geeft inspiratie.
Een ruimte als de koepel boven het Taj Mahal , het bekende 17e-eeuwse grafmonument te Agra in Noord-India, met een volledig marmeren afwerking en met een diameter van 20 m en een hoogte van 26 m, geeft door zijn lange nagalmtijd aan het geluid van een fluit een mystieke dimensie in een als het ware tijdloze ruimte. De akoestiek van sommige kerken neigt ons tot het verlagen van het stemvolume, als een soort akoestische verlegenheid om de rust ingrijpend te verstoren. Het oog kan daarbij het oor niet misleiden: hoewel de decoratie in barokkerken dikwijls meesterlijke nabootsingen bevat van marmer, zullen wij gehoorsmatig wel degelijk ondervinden dat er houtafwerking in de kerk aanwezig is. Zoals men door de vormgeving in de architectuur ook een bepaalde symboliek kan nastreven, zo ook kan de akoestiek ten dienste staan om een bepaald gedachtengoed te ondersteunen. Het ontwerp voor Hitlers Mosaiksaal in de Neubau der Reichskanzlei te Berlijn door Albert Speer is door zijn harde afwerking bedacht op het imponeren van de bezoeker, die geflankeerd door marcherende laarzen doorheen deze ruimte gaat, op weg naar de Führer. Men zou dit ideologische akoestiek kunnen noemen.
Men kan verder gaan in dit soort overwegingen. Zo kan geluid het ruimtegevoel ook sterk beïnvloeden: een binnenkoer krijgt een speciaal aspect door het veelvuldig weerkaatste geluid van een klaterend fonteintje. Wat men over al deze fenomenen ook kan zeggen is dat zij de dimensie tijd toevoegen aan onze visuele waarneming van de architecturale omgeving. Het zijn niet de gebouwen die spreken, het is de aanwezigheid van de gebouwen die de geluidsignalen beïnvloedt en een tijdsdimensie geeft. Kerken en kathedralen hebben dikwijls een langere nagalmtijd en die akoestische omgeving zet ons aan tot een zekere schroomvalligheid om de stilte te verstoren.
Wij herinneren ons de gebouwen vanuit ons visuele geheugen en we kunnen de omgeving met woorden beschrijven. Ons akoestisch geheugen is zwakker en ook de woordenschat er rond is niet zo uitgebreid. In dat verband werken meerdere onderzoekers vanuit de

linguïstiek aan de terminologie en de vertaling ervan in de context van de beschrijving van de geluidomgeving in de stad en het landschap.
Geluid kan ook domineren en het ruimtegevoel onderdrukken. In de buurt van een fontein hoort men alleen nog de fontein en nauwelijks nog het verkeerslawaai, de sound conditionering of ‘akoestisch behang’ (muzak) in winkelstraten en winkelruimten neemt elk auditief aanvoelen van de ruimte weg. Met een persoonlijke luider ingestelde mp3 speler wordt dit extreem en komt het functioneren in verkeer en maatschappij in gedrang. Auditieve signalen vanuit de omgeving worden niet of nog nauwelijks waargenomen. In dit laatste geval gaat het om maskering die de auditieve communicatie verdrukt. Dit treedt uiteraard ook op als er te veel lawaai is op de achtergrond zoals bij het eerder genoemde cocktailpartyeffect. In beide gevallen past de blootgestelde persoon zich aan door luider te gaan spreken met dientengevolge ook een verhoging van de grondtoon van onze spraak (het zogenaamde Lombard effect). Van stadsvogels als de tjsif-tsjaf is gelijkaardig aanpassingsgedrag bekend: in omstandigheden met luid stadsrumoer gaan de vogels luider of anders zingen of zij gaan inspelen op tijdelijk rustiger momenten of ze gaan eerder ’s avonds zingen.
Terugkomend naar de ervaring van ruimten en architectuur kan men zeggen dat het ontwikkelen van dit soort gevoeligheid voor het *spreken* van de ruimte het onderwerp is van wat men de aurale architectuur is gaan noemen. Het betreft het samenspel tussen architectuur en stedebouw en de auditieve ervaringen binnen die omgeving. Dit gaat om veel meer dan lawaaibeheersing en beantwoordt aan een duidelijk verbredende interesse binnen het akoestisch vakgebied. Voorbij de lawaaibeheersing werkt men nu aan de geluidkwaliteit en drukt men zich uit over de scherpte, de fluctuatiesterkte, de ruwheid van geluiden. Voor al deze aspecten worden ook maten ontwikkeld die toelaten om ontwikkelingen van producten uit de consumentenmarkt te sturen: geluid en audio in het interieur van wagens, de ‘sound’ van voertuigen... Finaal komen er meestal ook nog luisterpanels bij kijken.
In relatie tot de architectuur zijn een aantal tools ontwikkeld die de auditieve kwaliteit als doel hebben. We spreken hier van de virtuele akoestiek. Het geometrisch model, gecombineerd met de akoestische eigenschappen van de materialen, laat toe om het beluisteren van de akoestische signalen in deze omgevingen vooraf mogelijk te maken alvorens zij opgebouwd zijn. Deze tools vindt men momenteel terug in de akoestische advieswereld. Eens de geluidbron op afdoende wijze ingebracht is, kan men zich op luisterende wijze verzekeren van de akoestische kwaliteiten in concertzalen en andere akoestische omgevingen.
Men kan zo ook de interactie van een muzikale uitvoering virtueel in diverse akoestische omgevingen brengen zoals in het project ‘The Virtual Haydn’. De uitvoerder musicoloog Tom Beghin musiceert op zeven verschillende klavierinstrumenten in negen virtuele akoestische ruimten. Deze stemmen overeen met historische ruimten waarin Haydn moet weerklonken hebben.[ii]
In lopend onderzoek is ook verder gewerkt aan de implementatie van de eigenschappen van de luisteraar, gebruikmakend van al dan niet gepersonaliseerde HRTF’s (Head-Related Transfer Function). Op die wijze wordt informatie over de directiviteit van de geluidbronnen en de eigenschappen van de luisteraar aan de simulatie toegevoegd. Dit verhoogt het realiteitsgehalte van de simulaties, maar kan ook aangewend worden in de context van audiologisch werk rond binaurale perceptie en verbetering van (binaurale) gehoorprotheses.
De situatie in de buitenruimte is natuurlijk heel anders: de reflecties op de bodem of op het wegdek en op de gevels van de gebouwen leiden niet tot lange nagalmtijden en het wordt al wat moeilijker om een omgeving auditief te herkennen. Het geluidlandschap, de *soundscape*, is in de meeste gevallen het gevolg van niet akoestische specifieke elementen als stadsplanning en sociale activiteiten. Particulieren geluidbronnen als pratende, lachende, spelende personen, verkeer, natuurgeluiden, industrie, ... creëren samen het orkest van de stadsgeluiden, zonder dirigent evenwel. De ene keer met volledige bezetting, de andere keer met maar enkele ‘instrumenten’. De akoestische evaluatie van dergelijk stedelijk orkest is moeilijk eenduidig uit te voeren. De plaats van de waarnemer, het moment van de dag, het moment van de week... spelen een rol. De gebruikelijke evaluatie met kengetallen als bijvoorbeeld het achtergrondgeluidniveau is zeker niet afdoende. De appreciatie is immers

gekoppeld aan de verwachtingen en persoonlijke ingesteldheid. Het lijkt ook wat op de appreciatie van voedsel: de soundscape wordt ervaren als vervelend of monotoon als slechts een paar instrumenten meedoen, het wordt dan weer interessant en aangenaam wanneer de dosering in overeenstemming is met onze verwachting en onze persoonlijke smaak. Mogelijk zijn er soms te veel ‘ingrediënten’ en voelen wij ons dan eerder ongemakkelijk.
Het ruimere beheersen van de akoestische aspecten van de stedelijke omgeving wordt in de huidige benadering gezien als een onderwerp naast aspecten van veiligheidsgevoel, bereikbaarheid, thermisch comfort, windcomfort, verlichting, biodiversiteit, water in de stad,...
Op het vlak van akoestiek verlangen ontwerpers en beleidsmensen bij voorkeur eenduidige kwantitatieve parameters die kunnen aangewend worden bij het ontwerp en bij de controle achteraf. Maar dit botst met de realiteit. Maten voor de luidheid zijn onvoldoende: de tonaliteit van het geluid, het ritme van de geluidgebeurtenissen, de perceptie van kenmerkende geluiden, de invloed van de reflecties op omgevende gebouwen, zullen samen de context van geluiden bepalen. Vooral de context heeft een bepalende invloed op appreciatie of ongemak. Een holistische aanpak rond het in kaart brengen van de geluidomgeving is daardoor steeds meer in de aandacht. Multidisciplinaire samenwerking tussen stadsplanners, sociologen, psychologen, akoestici en wellicht ook geluidkunstenaars is hier aan de orde.
Algemeen kan men zeggen dat er een verruimd besef is ontstaan rond de auditieve ervaring van de omgeving die veel meer is dan pure lawaaibeheersing.
De *soundscape*, het geluidlandschap is de auditieve versie van het visuele landschap en soms ook het expliciet werken met geluid in de omgeving (*soundart*, geluidkunst). Er worden trouwens heel wat inspanningen gedaan om geluidlandschappen te detecteren, te categoriseren, te catalogeren[iii]. Met de moderne technologie is het immers vlot mogelijk om geluidbestanden te verzamelen en eventueel te koppelen aan fotografisch materiaal. Wanneer men beschikt over wat zorgvuldiger verzameld materiaal in de zogenaamde *soundwalks*, kan men ook binauraal werken en nog scherper psycho-akoestische kenmerken van de opnames koppelen aan de typologie van de openbare ruimte. De basisidee is evenwel dat de al dan niet tevredenheid over een auditieve omgeving samenhangt met de context die het verwachtingspatroon bepaalt. Niemand verwacht immers de akoestische kenmerken van het Arenbergpark op een plek als het Ladeuzeplein. Voor een gezellig terras zijn er akoestisch verwachtingen die verder reiken dan een ‘binair’ maximum toegelaten aantal decibel.

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[i] Barry Blesser,Linda-Ruth Salter, Spaces Speak, Are You Listening? Experiencing Aural Architecture, MIT Press,2007.
[ii] The Virtual Haydn Complete Works for Solo Keyboard, Naxos, 2009.
[iii] British Library, Archival Sound Recordings, http://sounds.bl.uk/

De akoestische omgeving: last of lust?

Invloed van de ruimteakoestiek op de spraakinspanning en op het spraakverstaan

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Inleiding

Een toespraak houden in de open lucht, buiten, is niet echt prettig: de stem draagt niet ver en al gauw gaat het rumoer de boodschapper overstemmen. Iedereen herkent die ervaring wanneer een stadsgids zijn verhaal in de openlucht moet doen: alleen de personen op de eerste rij kunnen goed volgen en om het verkeerslawaai te overstemmen moet de gids zeer luid spreken.

In die zin is een lokaal een **lust**: de reflecties van het stemgeluid zorgt voor ondersteuning en het lokaal schermt ons bovendien af tegen het omgevingsgeluid.

Maar wanneer deze reflecties al te lang blijven doorgaan, wordt dit ervaren als galm. Vanaf een bepaalde nagalmtijd ervaren we dat als storend en wanneer er bovendien meerdere sprekers zijn zoals op een receptie of in een cafetaria, ervaart men een galmend lokaal als extra nadelig. Het zogenaamde cocktail party effect gaat dan spelen: meer aanwezigen betekent meer lawaai, en meer lawaai betekent dat die aanwezigen ook nog eens luider gaan praten om zich verstaanbaar te maken. Zeker voor personen met verminderde gehoorkwaliteit en voor personen met een lager stemvolume wordt de situatie frustrerend: de zogenaamde conversatiecirkels worden steeds kleiner. Het lokaal is dan tot een last geworden. Buiten is het dan in die omstandigheden akoestisch een stuk beter ...

Het onderwerp van deze tekst is die delicate balans tussen lust en last.

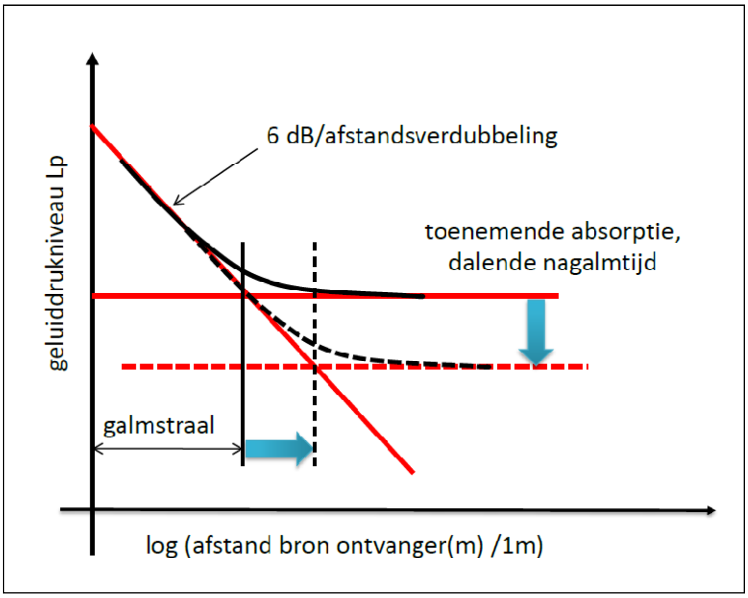
Dit kan niet zonder even schematisch de **ruimteakoestiek** te behandelen. In een tweede puntje behandelen wij de **steminspanning** in relatie tot het achtergrondgeluid en de ruimteakoestiek. Het hele proces van **spraakverstaanbaarheid** in de gesloten ruimte bekijken wij verder vanuit de signaal/ruis verhouding en de invloed ervan op de kwaliteit van de modulatieoverdracht. Dit heeft men samengebracht in één objectieve index **STI** waaraan men het hele verhaal kan ophangen.

Uiteraard zijn de karakteristieken van het bronsignaal bepalend, het is daar waar de spraakverstaanbaarheid begint. Dit is natuurlijk het verhaal van de articulatie en van het stemvolume van de spreker. Beide zijn persoonsgebonden, maar gerichte training kan en zal meestal ook helpen.

De ruimteakoestiek en de omstandigheden kunnen spelbrekers zijn. De mogelijke moeilijkheden kan men enigszins verhelpen door op een aantal zaken te letten: trager spreken -als het over een te lange galm gaat-, luider spreken -om maskerend geluid te overstemmen-, aandacht voor de correcte spreekrichting -waardoor sterker direct geluid in de richting van de toehoorder-, maar uiteindelijk zijn de remedies beperkt en soms ook vermoeiend.

Men doet dan al gauw liever beroep op elektroakoestiek -microfoon en luidsprekers-. Maar zelfs dan nog kan het moeilijk zijn om behoorlijke spraakverstaanbaarheid te realiseren: denk maar aan omroepsystemen in akoestisch moeilijke omstandigheden zoals in de ontvangsthal van een spoorwegstation. Deze korte tekst behandelt schematisch de inzichten en technieken rond deze materie.

Ruimteakoestiek



Figuur 1 Schematische voorstelling van de afname van het geluiddrukniveau met de afstand tot de bron in het geval van een diffuus geluidveld. Dit laatste kan alleen wanneer de geluidabsorptie in een lokaal gelijkmatig verdeeld is, en de ruimtevorm niet te erg van de kubusvorm afwijkt.

Het geluidveld in een gesloten ruimte wordt gekenmerkt door de aanwezigheid van een direct veld in de omgeving van de geluidbron en een galmveld wat verder weg. Het geluiddrukniveau vlakbij de bron neemt af met 6 dB per verdubbeling van de afstand tot de bron. Op een zekere afstand -de galmstraal- is het geluid van beide even sterk. Verder dan de galmstraal wordt het geluiddrukniveau volledig bepaald door de reflecties in de ruimte. Men zou kunnen zeggen dat het directe veld de zone is van goede spraakverstaanbaarheid en dat de zone van het galmveld een spraakverstaanbaarheid heeft die afhangt van de nagalmtijd die er heerst. Hoe korter de nagalmtijd, hoe lager het geluiddrukniveau in het galmveld en des te verder het directe veld zich uitstrekt.

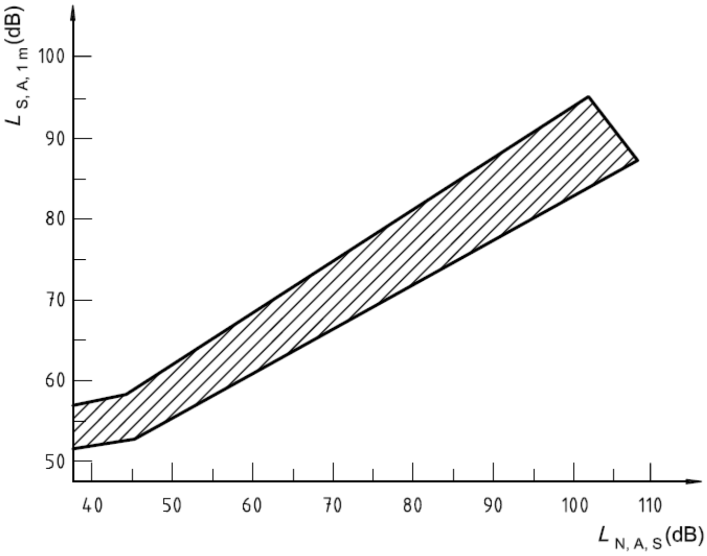
In principe neemt het geluiddrukniveau in het galmveld niet verder af met de afstand tot de bron. Maar dit geldt alleen in ruimten waar sprake is van een diffuus geluidveld. Dit is een geluidveld waarbij het geluid vanuit alle richtingen met gelijke sterkte op de ontvangers invalt. Dit zijn omstandigheden die men eerder in een galmkamer kan realiseren, maar in werkelijkheid is er in elk auditorium ook voorbij de galmstraal een verdere afname van het geluiddrukniveau met de afstand. Deze laatste is des te groter naarmate er meer geluidabsorptie in de ruimte aanwezig is. Als de geluidabsorptie toeneemt daalt dus de nagalmtijd en verdwijnt uiteindelijk het galmveld. Het geluiddrukniveau neemt in die omstandigheden gewoon af met 6 dB per verdubbeling van de afstand zoals dat het geval is in een vrij veld. Een dergelijk auditorium wordt omschreven als "te droog". Een "te galmend" auditorium wordt gekenmerkt door een lange nagalmtijd, een korte galmstraal en een eerder beperkte afname van het geluiddrukniveau met de afstand.

Steminspanning en achtergrondgeluid

Vocal effort	$L_{S,\,A,\,1\,m}$ dB
Very loud	78
Loud	72
Raised	66
Normal	60
Relaxed	54

Figuur 2 Steminspanning van een mannelijke spreker gemeten als equivalent geluiddrukniveau in dB(A) van lopende spraak gemeten op 1 m afstand, frontaal voor de mond van de spreker. (bron: EN-ISO 9921:2003 Ergonomics — Assessment of speech)

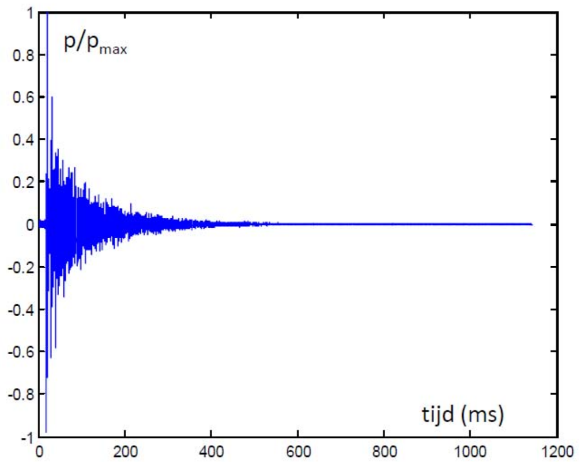
Het is reeds lang bekend dat voor een spreker-luisteraar-afstand van 1 m bij de ontvanger een voorkeursniveau van ongeveer 50 dB(A) geldt en dit wanneer er geen geluid is op de achtergrond. Wanneer het achtergrondgeluid boven de 40 dB(A) uitkomt, dan wenst men de spraak wat luider te horen. Overeenkomstig Figuur 3 komt dit neer op een toename van ongeveer 5 dB voor een toename van het achtergrondniveau met 10 dB. Zowel bij de spreker als bij de ontvanger geldt deze vorm van compensatie. Voor de ontvanger is dit het geval wanneer hij in een experiment zelf de controle heeft over het geluidniveau, voor de spreker gebeurt dat door zijn eigen aanvoelen van de situatie.



Figuur 3 Steminspanning als functie van het equivalent achtergrondgeluidniveau in dB(A) gemeten ter plaatse van de spreker (spreekniveau in dB(A), equivalent, frontaal, op een meter afstand van de mond). De gearceerde zone verwijst naar de spreiding voor verschillende sprekers. (bron: EN-ISO 9921:2003 Ergonomics — Assessment of speech)

Steminspanning en ruimteakoestiek

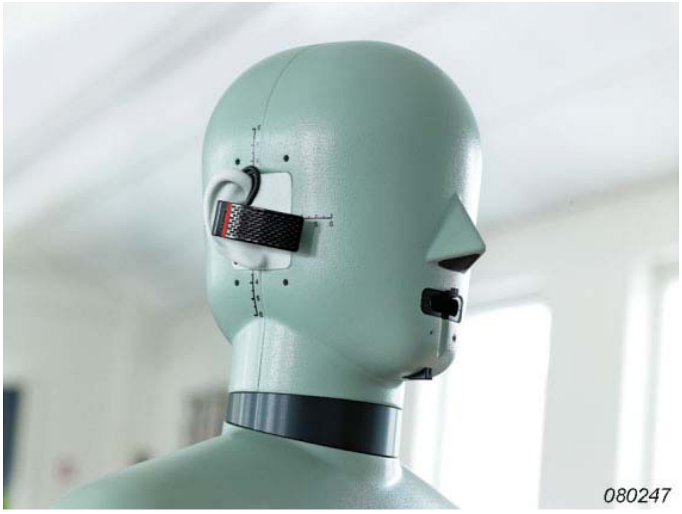
Over de interactie met het lokaal waarin alles zich afspeelt is minder bekend. Algemeen kan men zeggen dat verhoogde steminspanning geassocieerd wordt aan het feit dat de spreker zich oncomfortabel voelt. Dit kan een gevolg zijn van de werkomstandigheden, bijvoorbeeld rumoer in een klas, maar anderzijds kan er ook een terugwerking zijn van de fysische akoestische omgeving die de spreker verplicht om luider te praten. Het is op dit laatste dat wij nu even ingaan.



Figuur 4 Voorbeeld van een impulsresponsie bron-ontvanger in een ruimte met een nagalmtijd van 0,8 s.

De impulsresponsie van bron naar ontvanger bevat essentiële informatie over het traject van het geluid van bron naar ontvanger. Men leest erop af wanneer het direct geluid aankomt en wat de relatieve intensiteit en de aankomsttijd is van alle navolgende reflecties. Nagalmtijd en spraakverstaanbaarheid kunnen er perfect uit afgeleid worden.

Door de reflecties op de wanden ontvangt de luisteraar uiteraard meer geluidenergie dan in het vrije veld. Maar dit geldt ook voor de spreker zelf. In feite hoort hij zichzelf door de transmissie via de lucht en door beengeleiding. In een kamer komt daar de bijdrage van de reflecties bij. Het verschil kan men uitdrukken in dB. In principe kan dit ook afgeleid worden uit de impulsresponsie wanneer deze bepaald wordt met behulp van een hoofd/torso systeem. Dit op basis van de verhouding van het globale signaal dat de oren waarnemen, ten opzichte van het directe en dus zwakkere signaal, dat ze zouden waarnemen in een anechoïsche kamer. We noemen dat de versterkingsfactor in dB (G, gain in dB). In ruimten die wat groter zijn, kan men dit afleiden uit de vergelijking van de totale energie in de impulsresponsie tot deze in de eerste 20 ms bijvoorbeeld.



Figuur 5 Voorbeeld van een hoofd/torso systeem, hier voorzien van een telecommunicatie headset. (bron: Head and Torso Simulators, Brûel & Kjaer)

Daarnaast speelt zoals reeds gemeld ook het achtergrondgeluidniveau een rol. De spreker gaat zijn stem verheffen en dat heeft ook tot gevolg dat de fundamentele frequentie verhoogt (het zogenaamde Lombard effect).

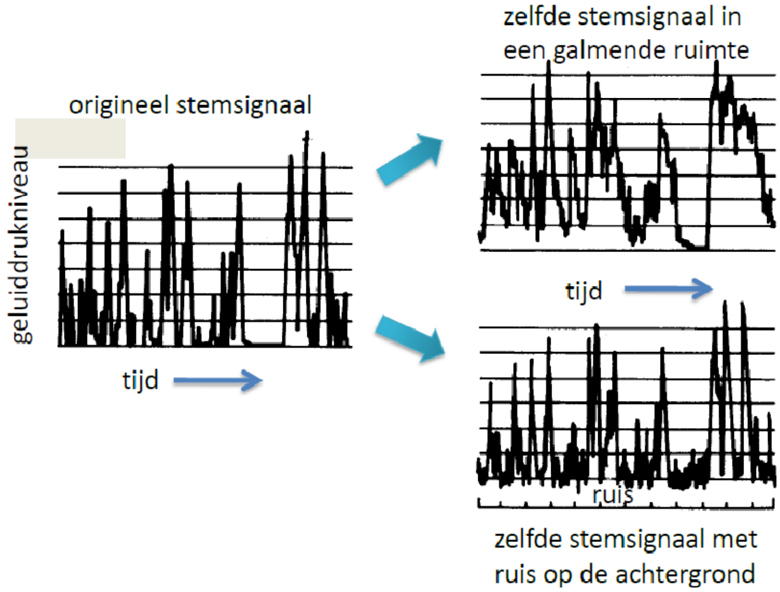
Verder valt te verwachten dat hun spreker ook reageert op het volume van de ruimte.

Recent is hieromtrent gewerkt in Denemarken, uitgaande van de registratie van de stem met een computerheadset-microfoon. Op deze wijze wordt het A-gewogen geluidvermogen van de spreker bepaald. (Brunskog, Gade, Bellester, & Calbo, 2009) onderzochten dit in zes uiteenlopende leslokalen met volumes van 100 m^3 (vergaderzaal,luisterkamer) - 2000 m^3 (auditorium) met nagalmtijd die varieerden van 0 (anechoïsche kamer) tot 1,5 seconden (auditorium met volume van 1220 m^3). Het achtergrondgeluidniveau varieert van 40-55 dB(A) (!). De G-waarden worden bepaald per octaafband en als één-getalswaarde wordt het gemiddelde van 125-4000 Hz gegeven. De waarden zijn klein en gaan van 0 (anechoïsche kamer) tot 1,12 dB (IEC luisterkamer). De geregistreerde sprekervermogens bestrijken een range van 0 dB (anechoïsche kamer is de referentie) tot -4,33 dB (in de vergaderzaal). De auteurs bevestigen de positieve correlatie van het sprekervermogen met het zaalvolume en een negatieve correlatie met de versterkingsfactor G. Het aangewende achtergrondgeluid is te zwak om tot besluiten te komen en ook van rechtstreekse relatie met de nagalmtijd is

geen sprake. Dit laatste is geen verrassing: het is de totale absorptie in de ruimte die de dissipatie van de geluidenergie bepaalt. Het is daarom een spijtig punt dat men in dit werk niet de relatie tot de totale absorptie A in de analyse heeft meegenomen: dit combineert het effect van volume (A is evenredig met V) en nagalmtijd (A is omgekeerd evenredig met T). Deze relaties zijn bekend onder de vorm van de (benaderende) formule van Sabine:
T = 0,16 V/A. en derhalve A= 0,16V/T (A in m^2; V in m^3;T in s).
We kunnen dus wel besluiten dat de ruimte op het toespreekvermogen inwerkt in een range van ongeveer -5 dB (met de anechoïsche kamer als referentiepunt 0 dB).

Ruimteakoestiek en spraakverstaanbaarheid

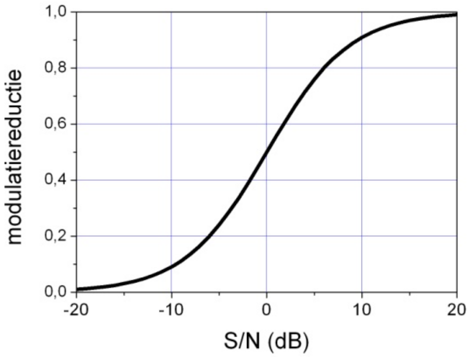
De kwaliteit van de spraakoverdracht wordt sterk bepaald door de signaal/ruis verhouding ter plaatse van de toehoorder. Deze wordt uitgedrukt in dB. Maar ook overdreven nagalm en storende echo's kunnen de spraakoverdracht sterk bemoeilijken. Al deze elementen zijn samengebracht in een globaal beoordelingssysteem dat door Nederlandse perceptie-onderzoekers ontwikkeld werd voor de bepaling van een kwaliteitsindex STI (speech transmission index) (Steeneken & Houtgast, 1980).
Deze bepaling vertrekt van de beoordeling van de kwaliteit van de transmissie van de amplitudomodulatie die in het stemsignaal aanwezig is.
Natuurlijke spraak kan in elk frequentiegebied (octaven van 125-8000 Hz) gekenmerkt worden door zijn amplitudomodulatie. Deze houdt verband met het spreekritme. Wie praat aan twee lettergrepen per seconde, heeft dus een amplitude die aan een ritme van 2 Hz oscilleert. Een meer gedetailleerde analyse levert een modulatiespectrum op in de octaaffrequenties F van 0,63-12,5 Hz.
In een anechoïsche stille kamer wordt de oorspronkelijke modulatie perfect doorgegeven: de modulatietransfertfunctie heeft de waarde m(F) = 1. Is er echter op de achtergrond een stationaire ruis aanwezig die alles overstemt, dan verdwijnt de modulatie en wordt de modulatietransfertfunctie m(F) = 0. In het eerste geval komt men uit op een spraakverstaanbaarheidsindex STI = 1; in het tweede geval is STI = 0.



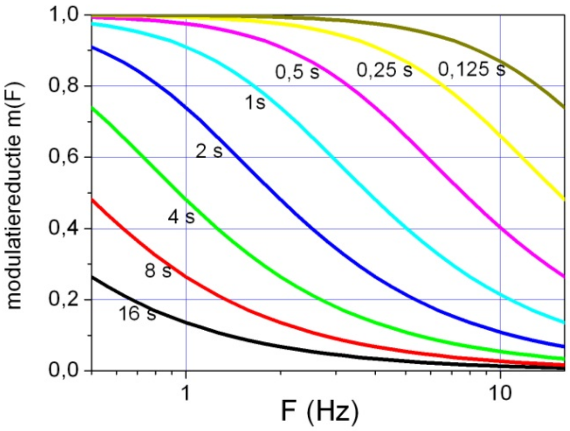
Figuur 6 Door nagalm wordt het oorspronkelijke signaal meer uitgesmeerd. In het geval van achtergrondgeruis wordt de modulatiediepte rechtstreeks beïnvloed.

In Figuur 6 worden de effecten nagalm en achtergrondgeruis geschetst. Het zal duidelijk zijn dat de aanwezigheid van geluid op de achtergrond de overdracht van de modulatiekwaliteit beïnvloedt. Waar het normale ongestoorde signaal fluctueert tussen een maximale waarde en een minimale waarde die de stilte benadert, zal het signaal in de gesloten ruimte niet terugvallen tot die minimale waarde. Dit zal bijvoorbeeld het geval zijn wanneer er in die ruimte sprake is van bijvoorbeeld installatielawaai. Hierdoor neemt het amplitudo van de modulatie af, en dit betekent voor de toehoorder een verlies in transmissiekwaliteit en dus moeilijker spraakverstaan.

Nagalm speelt een gelijkaardige rol. Het verschil tussen maximum een minimum daalt omwille van het uitgalmen van de ruimte. De ruimteakoestiek heeft dan tot gevolg dat de amplitudomodulatie daalt en dat daardoor ook de informatieinhoud van het signaal daalt.



Figuur 7 Modulatiereductiewaarden voor verschillende signaal/ruis verhoudingen.



Figuur 8 Modulatiereductiewaarden voor verschillende modulatiefrequenties en uiteenlopende nagalmtijd

Op Figuur 7 is bijvoorbeeld af te lezen dat voor een signaal/ruis verhouding gelijk aan 0 dB de modulatiereductie gelijk is aan 0,5. In dat geval wordt het spraaksignaal in zijn dynamiek gehalveerd.

Op Figuur 8 is het effect van de nagalmtijd te zien in functie van de modulatiefrequentie. Dit effect wordt natuurlijk kleiner bij lagere modulatiefrequentie -zoals trouwens ook bij trager spreken- en wordt groter bij langere nagalmtijd.

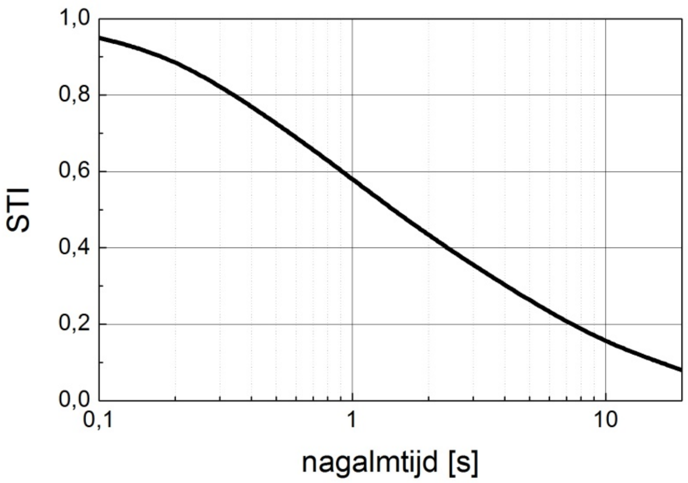
Er is een meet- en interpretatiesysteem ontwikkeld dat gebaseerd is op 7 frequentiebanden en telkens 14 modulatiefrequenties. Een wegingsschema laat toe om alles samen te ballen in één index namelijk de “Speech Transmission Index”. (IEC, 2003) Een vereenvoudigde variant is gebaseerd op slechts twee frequentiebanden (500 Hz en 2000 Hz) met telkens respectievelijk vier en vijf modulatiefrequenties (gaande van 1,02-11,63 Hz). Dit systeem leidt tot de bepaling van RASTI (Rapid STI).

De (RA)STI varieert tussen de waarden 0 en 1. De overeenstemmende beoordelingsschaal is in de onderstaande tabel gegeven.

Beoordeling van de verstaanbaarheid	excellent	goed	redelijk	zwak	slecht
STI	> 0,75	0,6-0,75	0,45-0,6	0,30-0,45	< 0,30

STI en nagalmtijd

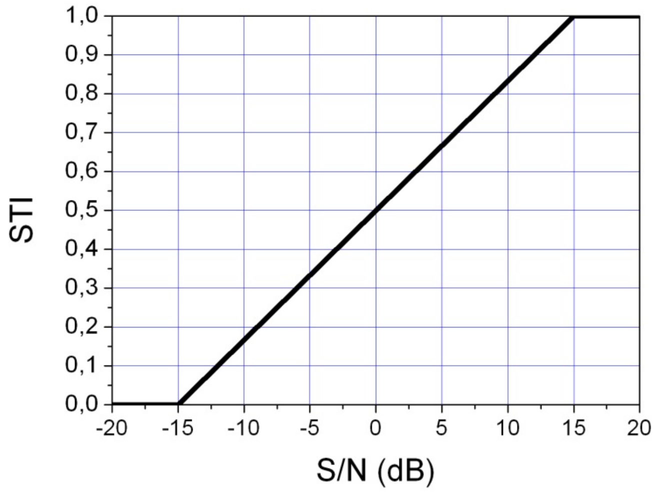
Hoewel de relatie tussen de spraakverstaanbaarheid en de nagalmtijd voor elke ruimte apart moet bekeken worden, willen we toch enkele globale relaties vooropstellen. We gaan daarom uit van een ruimte die gekenmerkt wordt door een exponentieel verloop van de nagalm en waarvan de nagalmtijd in elke frequentieband gelijk zou zijn. Het toepassen van de STI- evaluatie leidt tot de grafiek van Figuur 9. Opvallend is alvast dat in ruimten met een "normale" galm (rond 1 s) niet meer moet verwacht worden van een "goede" spraakverstaanbaarheid. Voor een "excellente" spraakverstaanbaarheid moet men in de richting gaan van een toch wel zeer korte nagalmtijd (< 0,4 s!). Dit laatste kan in tegenspraak zijn met de wens om enige natuurlijke terugkoppeling van de ruimte te hebben en met de nood om ook dieper in de ruimte een voldoende sterk signaal te hebben.



Figuur 9 Berekende verloop van de spraakverstaanbaarheidsindex STI voor een zuiver exponentieel en frequentieonafhankelijk verloop van de nagalmtijd.

STI en achtergrondgeluid

Als er een verstoring zou zijn met achtergrondgeluid dat in alle banden dezelfde signaal/ruis verhouding zou opleveren, dan verloopt de STI- waarde zoals opgegeven in Figuur 10.



Figuur 10 STI als functie van S/N als er alleen sprake is van verstoring door achtergrondruis (S/N dezelfde in alle banden).

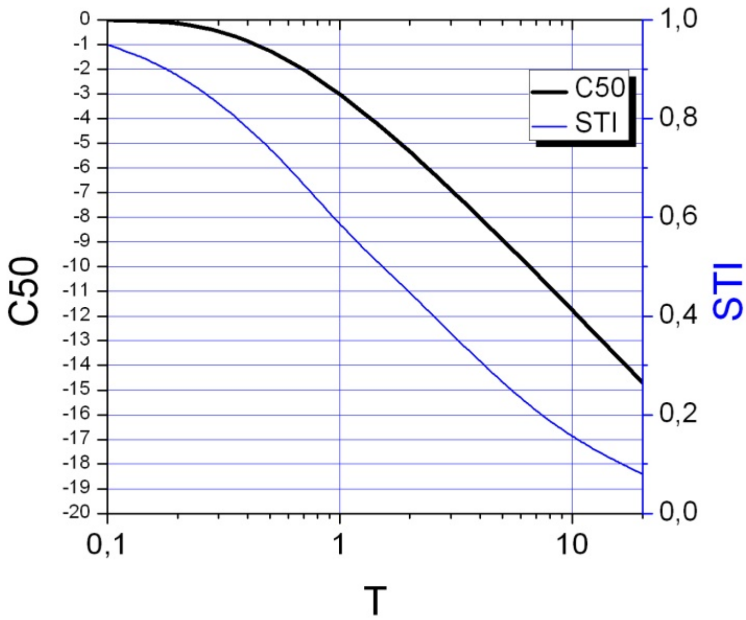
STI en andere indices

De amplitudomodulatie-transfertfunctie kan ook afgeleid worden uit de impulsresponsie. Deze impulsresponsie kan op verschillende manieren bekomen worden, maar momenteel is het gebruikelijk om te vertrekken van de responsie op een deterministisch ruissignaal of een sinussweep die door de bron uitgezonden wordt. Eens de impulsresponsie bekend, kan m(F,i) afgeleid worden en kan het STI algoritme toegepast worden. Effecten van de late reflecties en echo's kunnen zo op een toch zeer goed onderbouwde wijze in de beoordeling van de globale impulsresponsie betrokken worden. Op deze wijze laat het STI-meetprincipe zich toepassen op gelijk welk systeem voor spraaktransmissie. Het voordeel is dat de werkwijze gestandaardiseerd is en dat de te realiseren streefwaarden in een bestek kunnen opgenomen worden voor de levering van bijvoorbeeld een omroepsysteem.
Maar er zijn ook eenvoudigere benaderingen, die gewoon uitgaan van een opdeling van de impulsresponsie in een voor de spraakverstaanbaarheid "nuttig" deel en een daarna volgend "storend” deel. Zo heeft men bijvoorbeeld de Clarity (C50). Deze is betrokken op de vergelijking van de geluidenergie die aankomt in de eerste 50 ms na aankomst van het directe geluid ten opzichte van alles wat aankomt. Deze waarde wordt in dB gegeven volgens de formule:

$$C_{50} = 10 \lg \frac{\int_0^{50\,ms} p^2(t)dt}{\int_0^{\infty} p^2(t)dt} \text{ [dB]} .$$

Uitgaande van een exponentieel verloop kan men de waarde bekomen die op de grafiek van Figuur 11 zijn uitgezet. Deze grafiek laat toe om het onderling verband tussen de grootheden te plaatsen.

Deze verbanden zijn zuiver indicatief omdat ze gebaseerd zijn op een gelijkmatige exponentiële afname van de geluidenergie tijdens het nagalmproces . In principe is dit alleen mogelijk in een perfect diffuus geluidveld in een niet al te grote kamer.



Figuur 11 C50 en STI als functie van T voor een zuiver exponentieel verloop van de nagalm.

Akoestische streefwaarden

In het belang van de goede spraakverstaanbaarheid en het akoestisch goed aanvoelen van ruimte dient de nagalmtijd dus beperkt te blijven. Het is dus logisch om maximaal toelaatbare waarden voor ogen te hebben. Hetzelfde geldt voor het achtergrondgeluidniveau. Dit is een verplichting waar beter geen excuses of uitstel voor mogelijk zijn.

Er wordt dus best gesteund op wettelijke performantievereisten voor het gebouw bij de oplevering ervan.

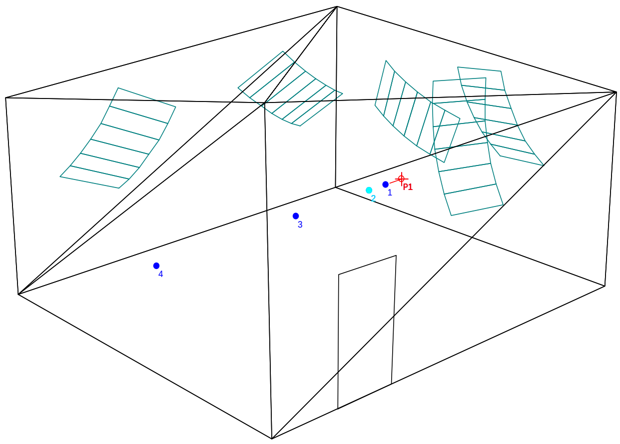
Als voorbeeld nemen wij de vereisten voor de schoolomgeving gebaseerd op (Shield & Hopkins, 2004).

Dit document bevat voorschriften en richtlijnen voor het akoestisch ontwerp van scholen in het Verenigd Koninkrijk. Dit zijn wettelijke verplichtingen.

Momenteel worden dergelijke specificaties voorbereid in het kader van de nieuwe Belgische norm NBN S01- 401 Schoolgebouwen.

lokaal functie	maximaal geluiddrukniveau[1]	maximale nagalmtijd[2]
Kleuterklas	35	0,6
Lagere school	35	0,8
Gymnasium	40	1,5
Refter	45	1,0

Simulaties en illustraties



Figuur 12 Een ruimtelijk model van de nagalmkamer aan de K.U.Leuven. Volume 196 m³ met gebogen reflectoren voor diffusie. Voorbeeld van een auralisatie voor verschillende afstanden tussen bron en ontvanger.

De stand van het onderzoek in deze materie laat de auralisatie toe. Dit wil zeggen dat de modellen toelaten om de impulsresponsies in zekere mate te voorspellen. Men kan ze dan ook gaan beluisteren en er alle criteria uit berekenen. De voordracht wordt geïllustreerd met virtuele luister-voorbeelden op verschillende afstanden van een spreker. Als voorbeeldruimten gebruiken wij de nagalmkamer van de K.U.Leuven en ook een veel groter kerkvolume. Daarnaast wordt ook de problematiek van de "luidruchtige" ruimten als cafetaria en restaurants als voorbeeld gehanteerd.

Figuur 13 Omstandigheden waarbij meerdere personen samen verschillende gesprekken voeren worden dikwijls als akoestisch problematisch genoemd. Het hogere achtergrondgeluidniveau heeft te maken met de veelheid van bronnen en met een neiging tot luider spreken. Beperken van de nagalmtijd en onderlinge afscherming van lagere bezettingsgraad zijn de enige mogelijkheden om de problemen in te perken.

[1] deze betreft het equivalente A-gewogen geluiddrukniveau over een relevante meetperiode van 30 min; het omvat geluid dat van buiten afkomstig is en van de gebouwinstallaties op vol debiet; het omvat niet het geluid van onderwijsactiviteiten, van het gebruik van uitrusting en van regenval.

[2] nagalmtijd in seconde; gemiddelde waarde voor de octaafbanden van 500, 1000, 2000 Hz.

Samenvattend

Samenvattend kunnen we stellen dat de ruimte in een belangrijke mate bijdraagt tot het geluiddrukniveau. Het is ook erg nodig om de directe geluidgolf van de spreker te ondersteunen.

Er is ook sprake van een zekere terugkoppeling tussen de spreker en de spreekruimte: deze is op een maximum van ongeveer 5 dB begroot. De spreker levert dus tot 5 dB minder geluidvermogen af ten opzichte van wat hij op dezelfde wijze vertelt in een anechoïsche kamer.

Tot hier is het lokaal dus een lust.

Maar overdreven galm en een te hoog achtergrondgeluidniveau kunnen spelbreker zijn. De spraakverstaanbaarheid kan dan in het gedrang komen.

De methode om de spraakverstaanbaarheid te begroten is besproken: de combinatie signaal en achtergrondruis kan tot de één-getalswaarde STI herleid worden. Men kan deze methode hanteren om prestatieëisen voor een minimale STI voorop te stellen.

Maar pragmatisch komt het er eerder op neer dat men op de gepaste plaats (nationale bouwvoorschriften en specifieke bouwbestekken) adequate vereisten oplegt aan de toelaatbare nagalmtijd (of vereiste absorptie) en aan de toelaatbare achtergrondgeluidniveaus. Hiervan hebben we een voorbeeld gegeven, gerelateerd aan de schoolomgeving.

Tot slot hebben we ook de toepassing van de simulatieprogrammatuur als illustratie aangewend.

Referenties

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